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DEPARTMENT OF AVIONICS

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QUALIFICATION PAPER

(EXPLANATORY NOTES)
FOR THE DEGREE OF "BACHELOR"
SPECIALITY 173 "AVIONICS"

Theme: "Implementation of a Survey-Comparison Navigation Method Using Three-Dimensional Digital Terrain Images"

Done by: student of the АВ-410Ба group, Pospielov Vitalii Mykhailovych
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Kyiv 2024

МІНІСТЕРСТВО ОСВІТИ І АУКИ УКРАЇНИ
НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ
ФАКУЛЬТЕТ АЕРОНАВІГАЦІЇ, ЕЛЕКТРОНІКИ ТА ТЕЛЕКОМУНІКАЦІЙ
КАФЕДРА АВІОНІКИ

ДОПУСТИТИ ДО ЗАХИСТУ
Завідувач кафедри
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КВАЛІФІКАЦІЙНА РОБОТА

(ПОЯСНЮВАЛЬНА ЗАПИСКА)

ВИПУСКНИКА ОСВІТНЬОГО СТУПЕНЯ "БАКАЛАВР"
ЗА СПЕЦІАЛЬНІСТЮ 173 "АВІОНІКА"

Тема: "Імплементація оглядово-порівняльного методу навігації на основі цифрового тривимірного зображення земної поверхні"

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Київ 2024

NATIONAL AVIATION UNIVERSITY

Faculty of Air Navigation, Electronics and Telecommunications

Department of avionics

Specialty 173 “Avionics”

APPROVED

Head of the department

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«___»___________2024

TASK

for qualification paper of the student

<u>Pospielov Vitalii Mykhailovych</u>

1. Theme: “Implementation of a Survey-Comparison Navigation Method Using Three Dimensional Digital Terrain Images”, approved by order 385/ст of the Rector of the National Aviation University of 14 March 2024.

2. Term of work execution: from 13 May 2024 to 16 June 2024.

3. Output data of graduation work: survey and comparative navigation systems, sensors for survey and comparative navigation systems, three-dimensional image formation systems, automatic ground object recognition systems.

4. Content of explanatory notes: Content; List of conditional terms and abbreviations; Introduction; Description of modern navigation methods, revealing their main advantages and disadvantages; Analysis of survey and comparative navigation systems; Principle of formation of a digital three-dimensional image of the earth's surface; Recognition of navigational reference points in survey and comparative navigation systems; Conclusion; References.

5. The list of mandatory graphic materials: figures, graphs, algorithms.

6. Planned schedule

№	Task	Duration	Signature of supervisor
1.	Justification of the diploma work topic	13.05.2024	
2.	Reviewing and processing the literature on the topic of research	14.05.2024	
3.	Analysis of survey and comparative navigation systems	16.05.2024	
4.	Three-dimensional ground objects image forming system	21.05.2024	
5.	Recognition of navigational reference points in survey and comparative navigation systems	25.06.2024	
6.	Checking for academic integrity and receiving a review of the diploma	31.05.2024	
7.	Preparation and printing of an explanatory note	02.06.2024	
8.	Preparation of the presentation and report	05.06.2024	

8. Date of assignment: "13" May 2024

Supervisor ______________ O.O. Chuzha

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The task for performing was accepted by ______________ V. M. Pospielov

(signature) (surname, name, patronymic)

ABSTRACT

Explanatory notes to graduation work “Implementation of a Survey-Comparison Navigation Method Using Three-Dimensional Digital Terrain Images” includes:

Key words: navigation, survey-comparative method of navigation, laser system; three-dimensional images, time interval, LADAR.

The object of the research: implementation of automatic and autonomous survey-comparative navigation system.

The subject of the research: principle of formation of a three dimensional image of the ground reference points.

Purpose of graduation work: to ensure the redundancy of navigation information by implementation of an automated and autonomous navigation system based on a survey-comparative method of navigation by forming a three-dimensional image of the earth’s surface.

Research methods: to analyze and solve the set tasks, statistical methods of data processing, comparative analysis; decision-making theory and abstraction methods were used.

Scientific novelty: using sensors of technical vision, namely “LiDAR” technology to implement the survey-comparative method of navigation on modern aircrafts.

CONTENT

LIST OF ABBREVIATIONS

INS – Inertial Navigation System

GNSS – Global Navigation Satellite System

SCNS – Survey-Comparative Navigation system

GPS – Global Position System

AES – Artificial Earth Satellites

3D – Three dimensional

LiDAR – Light Detection and Ranging

RMS – root-mean square error

UAV – Unmanned Aerial Vehicle

MRR – Matrix Radiation Receiver

LSFTDI – Laser System for Forming Three-Dimensional Images

BEF – Basic Element of the Form

TIM – Time Interval Matrix

INTRODUCTION

Actuality. Nowadays, the fastest growing type of transportation is aviation. Numerous advantages compared to other types of transportation lead to an ever-growing interest in air transportation services. Statistics shows a steady increase in demand for aviation services, resulting in a rapidly growing number of flights. The widespread use of aircrafts and their intensive flights in airspace leads to increasing of the requirements for the accuracy and reliability of navigation decisions in risk conditions.

Accurate determination of aircraft coordinates is the main tasks of modern navigation. The classical version of the integrated navigation system consisting of GNSS and IRS has a number of drawbacks and limitations. It is known, that the IRS systems have the property to accumulate path calculation errors over time, which are corrected by GNSS, however, unreliable operation in areas with unstable satellite direction finding and the possibility of intentional or accidental jamming of the satellite radio signal require the development and implementation of alternative navigation systems that take these risks into account.

That’s why, there is a need to implement an additional navigation system that could ensure greater flight safety by creating redundancy of navigation information. The survey-comparative navigation system can be used to provide this necessary redundancy.

The essence of survey-comparative navigation method - is to determine the location of an aircraft by comparing the terrain or ground reference points, coordinates of which are known, depicted on a map or saved in the memory of navigational computing device with their actual observed view and if there is a match, determine the aircraft position.

Modern survey and comparative systems are autonomous and provide integral reproduction of the full set of navigation data, interact with on-board digital computers. Moreover, they also have the possibility to correct other navigation information sensors and systems, for example - IRS.

That’s why, the current stage of technological and scientific progress defines automatic terrain recognition as one of the priority research areas for the creation and improvement of automatic survey-comparative navigation systems, which can be fully realised with the help of technology of formation of the three-dimensional images of ground reference points.

CHAPTER 1

THEORETICAL ANALYSIS OF EXISTING NAVIGATION SYSTEMS

1.1 General information about navigation and navigation methods

Different navigation systems are used in the aviation industry depending on the purpose and use of the aircraft. The capabilities of aviation navigation are largely determined by the accuracy and reliability of solving navigation problems, the level of development of navigation aids and systems, including radio navigation devices and systems. First of all, the navigation system which is used in civil aviation, must ensure safety and reliability, as well as air traffic economy. In addition, aviation navigation systems must be unified at all stages of flight to reduce the amount of equipment on board and at the ground stations, as well as in space. At the same time, they must also be able to clearly determine the route, distance to the destination, and deviations from the specified course.

The essence of the navigation process: primary information devices measure various physical parameters that depend on the position and movement relative to the selected system of coordinates, which is tied to the earth's surface. Information processing devices, based on this data determine the navigation parameters that characterize the speed and coordinates of the object's location relative to the chosen reference system. Thus, information about: primary parameters, the selected coordinate system, as well as information about the shape of the Earth (its magnetic and gravitational fields) is necessary for the navigation during a controlled flight.

Pilots use navigation systems and means to determine where they are going and how to get there. Although the basic requirement of a navigation system is to guide the crew from point A to point B, increased traffic density and airline economics means that more than one aircraft is planning a specific route. Flight planning takes into account such things as favorable winds, popular destinations and schedules. Aircraft navigation is therefore also concerned with the management of traffic and safe separation of aircrafts.

It is obvious, that the increase in requirements for positioning accuracy in the airspace and the introduction of new more accurate navigation characteristics are noted in global and regional aviation development plans. Improvement of the navigation accuracy is a key task in supporting the growth of air transportation in terms of ensuring the required level of air transport safety.

The main tasks of air navigation include:

1) Determination of aircraft navigation parameters: coordinates, altitude (absolute and relative), flight speed, course and other;

2) Creation of the best route to the destination. In this case, the main task of the navigation system is to help pilots get to their destination in the shortest possible time and with the minimal fuel consumption.

3) Control of the path and its correction when necessary;

4) Operational route correction during the flight. The need to change a flight route may arise in the event of an aircraft malfunction, in the presence of unfavorable meteorological conditions along the route, to avoid a collision with another aircraft.

There are various methods for determining aircraft coordinates, which can be classified into three main methods: path calculation method (dead reckoning), positioning method, and the oldest one – survey and comparative navigation method.

1.2 Dead reckoning navigation method

Path calculation method or dead reckoning is based on the continuous calculation of the aircraft trajectory, based on the data about velocity vector (integration over time of the measured velocity vector or acceleration relative to the Earth's surface) and the coordinates of the initial point of movement. Information about the speed of the aircraft can be obtained from inertial navigation system, Doppler speed meters, or from onboard system of air data. Knowing the direction of movement of the aircraft, wind speed and angle of drift, it is possible to obtain the velocity components in the selected system of coordinates, the integration of which provides information about the components of the aircraft traveled distance. It is important to note, that it is important to enter coordinates of the initial or starting point of the route, from which the path calculation starts. So, in dead reckoning navigation, the pilot starts from a known coordinates and uses wind parameters to calculate a heading to steer and an expected groundspeed in order to predict an arrival time over a desired point. Therefore, a Dead Reckoning Position (DR Position) - is a point in relation to the earth established by keeping an accurate account of time, ground speed, and track since the last known position. This point can also be obtained by applying wind effect to the true heading and true air speed of the aircraft.

On the principle of such dead reckoning method the Doppler, airborne, radar, and inertial navigation systems are based.

1.2.1 Doppler navigation system

As the first example of dead reckoning navigation method, a Doppler navigation will be observed. It uses the Doppler principle (the essence of which lies in changing the frequency of the received oscillations during the relative movement of the receiver and transmitter of these oscillations) to measure an aircraft's ground speed (speed relative to the ground) and the drift angle (angle between the aircraft longitudinal axis the actual direction of its movement, fig.1.1).

If the source of oscillations moves relative to the environment, then the distance between the wave crests (wavelength) depends on the speed and direction of motion. So, if the source reaches the emitted wave, the frequency of wave increases and wavelength decreases respectively, when source moves away from this wave, the wavelength increases. Obviously, the frequency shift is greater the greater the speed of the receiver relative to the transmitter.

The same effect occurs if the transmitter and receiver are stationary relative to each other and are located on a moving object. In this case, the oscillations (signal) are received after reflection from the earth's surface. During the flight, the area of the earth's surface, which is irradiated by the system antennas, moves relative to the aircraft at a speed equal to the airspeed of the aircraft.

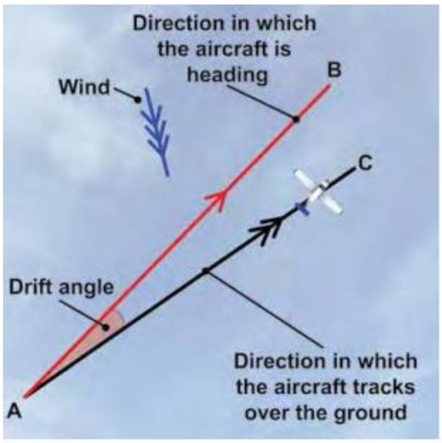

Fig. 1.1 Drift angle formation

The Doppler radar, functions by continuous measurement of Doppler shift and converting the measured values to groundspeed (V_g) and drift angle (β_{dr}).

The received data is sent to the navigation system to determine the coordinates of the aircraft using the path calculation method and to the indicator of the ground speed and drift angle. So, the frequency of the radio waves reflected from the ground received by the Doppler navigation system receiver differs from the frequency of the radio waves emitted by the transmitter. The difference in these frequencies is used to determine the radial velocity of the aircraft, taking into account the orientation of the antenna beam relative to the aircraft, ground speed and drift angle can be determined. If the Doppler signal due to some circumstances is lost, the system automatically switches to dead reckoning, which can be characterized as "memory" operation of the system. In this case, system uses measured airspeed corrected by the last determined wind vector.

Schematic diagram of three-beam (to improve equipment accuracy they are emitted in different directions) Doppler speed and drift angle meter, which uses non-modulated continues signal is shown on figure 1.2:

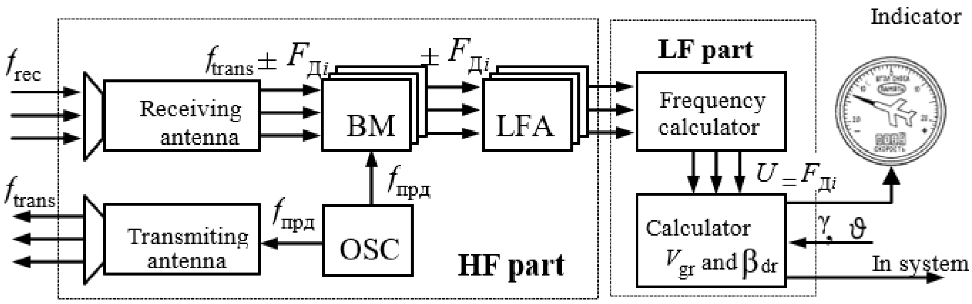

Fig. 1.2 Principle of Doppler speed and drift angle meter

The main functional elements of such equipment are: a high frequency generator or oscillator (OSC); transmitting and receiving antennas that form an antenna-waveguide system; a balance mixer (BM); and a low frequency band-pass amplifier (LFA), structurally combined into a high-frequency block (HF block).

The principle of its work is as follows: the electromagnetic oscillations of the required power with a frequency f_{trans} are generated by an oscillator, pass through the waveguide-slot bridge and divide into three signals and are radiated by the transmitting antenna in form of three narrowly directed beams. Signals reflected from the earth's surface with frequencies $f_{trans} + F_Д$ are received by receiving antenna and enter the paths of three identical receiving and measuring channels, consisting of BM and LFA. The input of each channel also includes signals from the oscillator, which provides reference signals. At the outputs of the BM low-frequency signals are sent to the amplifier. Then signals enter the low-frequency part, in the frequency calculator the average Doppler frequency is calculated. The voltages proportional to the average Doppler frequency values send to the calculator, which taking into account data on the roll (γ) and pitch (ϑ) of the aircraft, as well as the data on the angular orientation of the antennas beams, calculate the values of the ground velocity and the drift angle [1].

A Doppler navigation system has the following advantages:

1) this system is autonomous and requires no ground based or space navigation aids;
2) is usable worldwide. System is resistant to signal-jamming, which allows the system to operate well in areas that are “off the grid”;
3) performs determination of navigation parameters with high accuracy, so it very accurate overland;
4) this system provides a relatively fast speed measurement, which gives the possibility for pilots to react quickly;
5) it doesn’t depend on weather conditions and the system does not require any preflight alignment.

But, of course, this system also has some drawbacks: the surface winds and ocean currents move the water surface in random directions, so it is less accurate during flight over the seas and oceans; there are also limitations over some rough terrains. But the most important its downside is that it only works very effectively at relatively low altitudes. The higher the aircraft altitude, the further away it is from the topography that its radar signals must bounce off of. Moreover, during the processes of climbing and descent, as well as during manoeuvers of the aircraft with roll and pitch angles more than 5...10° the accuracy of determining the speed and angle of drift is significantly reduced.

The latest improved Doppler Navigation Systems combine the inherent accuracy of ground speed and drift measurement with information from IRS, Loran C, GNSS (GPS in particular) and VOR / DME, in various combinations to suit requirements for modern civil aviation.

1.2.2 Inertial navigation system

Nowadays, inertial navigation systems have become the basis of navigation systems for various moving objects. The inertial reference system (IRS) or inertial navigation system (INS) are used to determine the aircraft location, by determining its angular position in space. Its task lies in measuring the angles of aircraft yaw, roll, pitch, speed changes in angular parameters and linear accelerations (overloads). It also calculates the trajectory angle, true track angle, track speed, vertical speed, drift angle, wind direction and speed, geographical coordinates of the aircraft (latitude and longitude), as well as aircraft groundspeed. It is an autonomous dead reckoning method of navigation. These systems should be provided with a certain amount of initial information (about the surrounding fields, coordinate systems, etc.) to autonomously determine the navigation parameters necessary for control with the required accuracy during the movement of the object.

Inertial navigation systems (INS) were introduced into civil aviation during the early 1970s. System doesn't require any radio navigation inputs and it does not transmit any radio signals. Therefore, being self-contained, the system is ideal for long distance aircraft navigation over oceans and undeveloped areas of the globe.

Created platform-based inertial navigation systems are among the most reliable navigation aids used on moving objects, which have a wide functional capabilities range. With the development of manufacturing technologies, a subtype of INS appeared, the so-called platformless analytical INS, which gives the possibility to place its sensitive elements directly on the aircraft frame; mostly on all modern aircrafts such type systems are installed. Their main advantage is the reduced system weight, which gives the possibility to install it more simply and efficiently.

The procedure for determining the ground and vertical velocity of an object involves processing of accelerometer signals and their subsequent integration. In this case, the orientation of the accelerometer axes in in space must be known at each current moment of time (this condition is met either by installing the accelerometers on a controlled gyro platform or by calculating their orientation using information from gyroscopic devices). According to this information it is possible to determine the coordinates of the object's location in the specified coordinate system (geodetic, orthodromic, geocentric or other).

Gyros are used to determine information about the roll, pitch, yaw angles as well as accelerations and angular velocities.

With the help of certain algorithms, the angles of inclination, distance to a reference point with known coordinates, its azimuth, bearing and other navigation parameters can be also obtained.

The fundamental concept behind inertial navigation is: beginning from a known location, the system computes the current position (through continuous running, known as dead reckoning) in terms of both direction and speed traveled, originating from the initial coordinates. Inertial navigation systems (INS), utilizing mechanical gyroscopes, or inertial reference systems (IRS), employing laser or fiber-optic gyroscopes, differ from other navigation systems in the method of establishing aircraft direction, distance covered, and speed. Three linear accelerometers (one for each X, Y, or Z axis) determine accelerations, which are then integrated over time to ascertain changes in velocity. Double integration allows for the determination of the distance covered.

The INS basic components of an INS are: three linear accelerometers arranged orthogonally to supply X, Y, and Z axis components of acceleration; three gyroscopes to measure changes in aircraft angles and their value; a computing device for continuous calculation of aircraft navigation information.

On modern aircrafts the most widespread at the moment are IRS (has the possibility to provide the navigation data to the FMS) with ring laser gyros (figure 1.2.1). Such system consists of: Inertial Reference Unit (IRU), three laser gyroscopes and three micromechanical accelerometers; the control panel in the cockpit (Mode selector unit (MSU)), which allows pilots to choose between normal “NAV” mode (spatial positioning and navigation) and backup mode “ATT” (only spatial positioning); the backup power relay, which connects batteries if the main power supply fails. Laser gyroscopes provide information about the angular velocity along three axes, and accelerometers – about acceleration along the same axes. The general views of ring laser gyro are shown on figure 1.3:

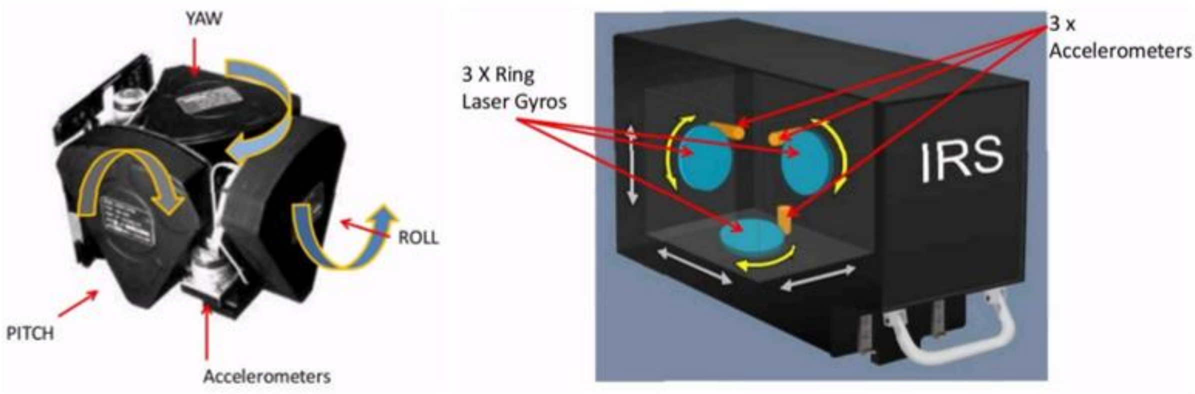

Fig.1.3

Basically, ring laser gyro (RLG) gives the same information as a gyroscope, but technically it is not a gyroscope since it has no moving parts. In general case, the principle of operation of laser gyroscopes is based on the Sangac effect: the optical paths of propagating in opposite directions ways in a rotating ring resonator are different. A RLG is made from a single block of glass with three holes, drilled through the glass to form a triangular path (figure 1.4).

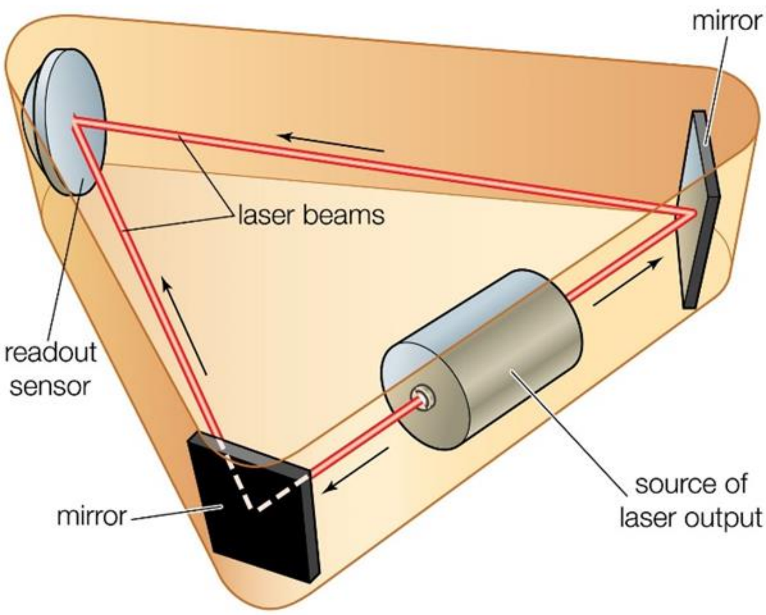

Fig. 1.4 Construction of the laser gyroscope

Two holes are plugged with mirrors and the triangular tube is filled with helium neon or other gas (the path difference between the beams is very small (~1 nm = 1×10^{-9} m)), therefore a source of high spectral purity and stability is required. When the gas is charged, it produces two counter-rotating light beams that are reflected around the path by the mirrors to detect the rotation. These beams emerge through the third hole and interfere, forming the so-called interference pattern. As the RLG moves, one beam has a longer path to travel in comparison to another, which causes changes in the interference pattern that are detected by photocells [2]. The frequency difference between these two beams causes interference fringes to move across the detectors at a frequency proportional to the frequency difference between the beams and hence, proportional to the input angular rate. At the output we get alternate signal, which frequency is proportional to the angular velocity of the resonator.

The advantages of inertial navigation systems include:

- INS system is completely autonomous, so it doesn't require either satellite or ground equipment;
- it has a very high interference immunity and is very accurate during short moments of time;
- this system also provides high informative data and can be used during all weather conditions.

But at the same time the INS systems have a very important drawback as it is subjected to accumulate a path calculation error over some period of time, so it must be adjusted from time to time using other navigation systems. INS methodological error lies in fact that the actual shape of the earth's surface is not taken into account during its operation.

1.3 Positional navigation method

A positional method is based on the use of position surfaces or position lines to determine the location of the desired object.

Where the position surface - is the geometric location of the points of the probable location of an object relative to the Earth's surface, where the physical parameter measured onboard the aircraft or from the Earth's surface has a constant value. The mathematical description of the position surface is as follows:

$$F = f\,(x, y, z),$$

where x, y, z are the coordinates of the aircraft location.

The properties of position surfaces are determined by the following characteristics: geometric shape f (x, y, z); displacement error (σ_{Π}) and; gradient (q). So, the geometric shape is obtained by constructing the function f (x, y, z) = const in the accepted reference system. The gradient characterizes the speed and direction of the fastest change in this function. Displacement error – is a RMS error of the position surface displacement relative to the point of the actual location of the aircraft.

To solve the navigation problem, three different intersecting position surfaces are required to determine the spatial position of the aircraft (three x, y, z coordinates). So, the intersection of two position surfaces with the Earth's surface will define the object location on the Earth's surface.

The position line - is a geometric location of projection points of the possible location of the aircraft on the Earth's surface. It is formed as a result of intersection of the position surface and the Earth's surface. The properties of such lines are the same as for position surfaces: geometric shape, gradient and RMS displacement error.

The following position lines are used in air navigation: line of equal azimuths (bearings); line of equal distances; line of equal distance differences; astronomical position line. It is important to note, that lines of position also include the "loxodrome", which crosses the geographical meridians at the same angles, and "orthodromy" – an arc of a large circle, which is the shortest distance between two points on the surface of the globe.

Positioning method is the basis for the construction of GNSSs; short-range and long-range radio navigation systems.

1.3.1 Short-range navigation system

Very high frequency Omni-directional Range or VOR was approved as the short range navigation aid in 1960 by ICAO. It permits pilots of all types of aircraft, to navigate easily and accurately from one VOR beacon to another. This system produces 360 tracks at 1˚ spacing which are aligned in relation to magnetic north from the VOR location. So, it determines the azimuth of the aircraft relative to the location of this beacon. An instantaneous range and bearing fix can be obtained if its frequency is paired with a DME (distance measuring equipment). The VOR beacon generates an amplitude-modulated total signal ($U \Sigma (t)$), in which the azimuth information is contained in the phase of the circular frequency. VOR beacons operate in the frequency range of 108-117,975 MHz. The range of the beacon depends on the radiation power and is equal to 50-370 km.

An aircraft's VOR receiver measures the phase difference (angular difference) between two signals from the VOR transmitter. Ground-based beacon has two antennas: an omnidirectional and an antenna with rotating directional diagram that create a rotary pattern in the form of a cardioid (limacon), figure 1.5. The VOR beacon transmits two signals at the same time: one signal is a 30Hz FM constant pattern (reference signal), which broadcasts in all directions (omni-directionally), producing a constant phase regardless of a receiver's bearing from the beacon; the other signal is an alternate pattern with 30 Hz amplitude modulated variable phase (alternate or directional signal), created by the rotating transmission pattern. The two signals are in phase on Magnetic North from the VOR beacon; in all other directions there is a phase difference between the two sets of signals which identify the magnetic bearing of the aircraft from the transmitter. In more simple words, the alternate phase of signal lags behind the constant one by an azimuth (angle between the North direction and aircraft heading). The on-board VOR receiver measures the phase difference between these two signals, and displays it as a bearing on the PFD display.

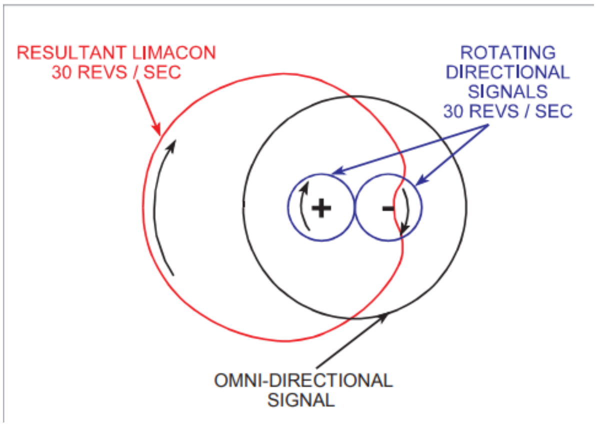

Fig. 1.5 Principle of formation of the VOR directional pattern

VOR has the following applications: marking the beginning, the end and centre line of airways or sections of airways; as a landing aid at airfields using published procedures; as a source of route navigational position lines. Moreover, this system provides the opportunity to: perform flight operations on a given azimuth; determine the position of the aircraft by the azimuths of two VOR beacons; correct navigation computers and listen to beacon recognition signals or voice communication signals.

To identify VOR beacons, the emitted signal is modulated with a Morse code or a speech call sign. The call signs are transmitted by the VOR transmitter to the intercom equipment and the pilot can monitor them by listening. For example, the United Kingdom VORs use 3 letter aural Morse, sent at approximately 7 groups/minute, at least every 10 seconds. This information is transmitted at the same time as the bearing information. The VOR receiver also receives signals from marker beacons. These signals clearly show the pilot how far away from the runway he is.

There are the following types of VOR systems:

- standard VOR;
- BVOR (broadcast VOR), which additionally provides weather and airfield information between beacon identification;
- DVOR (a Doppler VOR) - overcomes siting errors, thus increase the bearing accuracy;
- VOT – is a test VOR used to test an aircraft's equipment accuracy before the flight. A fixed omni-directional signal (a continuous tone or a series of dots) is broadcasted for a 360° test radial. Error more than +/-4° in bearing accuracy indicates that equipment needs servicing;
- VORTAC co-located VOR and TACAN beacons;
- TVOR (terminal VOR) has low power and is used at major airfields, usually as a locator in conjunction with an ILS equipment for a VOR approach procedure.

Error of azimuth measurement is within 1°-3.5° and largely depends on the nature of the terrain. All VOR beacons are monitored. So, the monitor will warn the control point and remove either the identification and the navigational signals or switch off the beacon if: bearing information error change exceed 1°; reduction of >15% in signal strength [3].

The VOR navigation system has the following advantages: is reliable in various weather conditions; provides a relatively accurate measurement of the aircraft's azimuth, allowing pilots to navigate with precision along the route and approach paths; system is widely available and provide coverage in many parts of the world.

At the same time, it also has a sufficient drawback, this system is largely depending on the nature of the terrain. The so-called line-of-sight limitations: signals can be obstructed by terrain or other obstacles, especially at low altitudes. Moreover, there are areas without the VOR signal coverage (oceans and remote mountains regions).

1.3.2 Global Navigation Satellite System (GNSS)

The original GNSS was the U.S.'s Global Positioning System (GPS), which still is the most widely used system all over the world. The success of GPS encouraged other countries to build their own GNSS, over the years, several similar systems have been developed: GLONASS, Compass, Galileo, IRNSS, QZSS, etc. So, the satellite navigation system provides the pilot and other systems with navigation data obtained by measuring signals from artificial navigation satellites. Because all the GNSSs use the same basic signals in the L band (long band 1-2 GHz), they can complement one another to provide increased accuracy. For improved precision of location, many receivers are capable of receiving both GPS and one or more other GNSS signals, and combining them.

GNSS consists of three segments: the space segment (constellation of satellites); command and control ground segment; user segment.

The space segment consists of a certain number of artificial Earth satellites (AES). They function is to emit navigation signals, which are used by the receivers to determine their location.

The command and control segment consists of ground-based stations located in different parts of the earth's surface in such a way as to provide a connection with all GNSS satellites. The ground stations monitor the position and parameters of each AES, because information about the exact location of each satellite is required to determine the user's coordinates. So, ground stations monitor the position of each AES using precise radar equipment and determine its position. Then, this information is transmitted to the satellite.

The user segment consists of an unlimited number of satellite signal receivers. The receiver contains a high-speed computer that performs the necessary calculations. The output of the receiver is a decimal display of latitude and longitude as well as altitude.

GPS is a US satellite-based radio navigational, positioning, and time transfer system. The system provides high-precision position, velocity information and precise time to countless appropriately equipped users around the world. GPS is unaffected by weather and provides a worldwide common grid reference system based on the Earth-fixed world geodetic system of 1984 (WGS-84) datum.

Each GPS satellite has two transmitters that together transmit time and position signals to each Earth-based receiver. One of the transmitters radiates a signal called L1 on frequency 1575.42 MHz. Each satellite also contains another transmitter on a frequency of 1227.6 MHz, the so-called L2 signal, which contains another pseudo-random code known as the “P” code, designed for use by only the military users, so military receivers are more accurate than the civilian (or enemy) ones, which receive only L1 signal. This feature is called selective availability (SA).

The, so-called, constellation, which consists of 24 satellites is designed in a way, that a minimum five of AESs are always observable by a receiver anywhere all over the world. The receiver uses data from a minimum of four of them above the mask angle (the lowest angle above the horizon at which it can use a satellite). All 24 GPS satellites transmit the signal on the same frequency, but the PRC is unique to each AES, so the receiver can easily distinguish them. The transmitted signal is a pseudo-random code (PRC) called a coarse acquisition code (C/A). Such codes contain information about satellite positions, GPS system time and accuracy of transmitted data. Knowing the speed at which a signal travels (approximately 186,000 miles per second) and the exact time of transmission, we can use the arrival time to calculate how far the signal travels [4].

The basic information contained in the L1 signal consists of: almanac data, ephemeris data, and the current date and time. Almanac data helps receivers initially focus on satellites signals as it effectively informs each airborne receiver about each satellite's position throughout the day. Ephemeris data contains the exact position and timing of each satellite. Time and date signals come from each satellite's atomic clock. All satellites, contain TT&C (Telemetry, Tracking and Control) unit. Ground stations use such equipment to transmit updated ephemeris data and ensure that satellites are in the desired position. Small motors on satellites are powered from the ground, allowing ground stations to correct small deviations in satellite position that lead to measurement errors.

GPS operation concept is based on the ranging and triangulation from a constellation of satellites in space which act as precise reference points – positional navigation method. A GPS receiver measures distance from a satellite to the receiver using the travel time of a radio signal. The determination of the location of an aircraft or its onboard GPS receiver is based on measuring the distances between the receiver and three satellites.

So, the basic concept of equipment operation is as follows: switched on onboard receiver receives continuous navigation signals from the satellites, as well as the almanac data, which is downloaded (interrupted signal is equal to loss of connection with the satellite). Such almanac contains information about each satellite position at certain moments of time. Then, receiver match each satellites coarse acquisition code with contained in the memory its identical copy. By shifting the copy of the signal, and comparing this shift with its internal clock, the receiver calculates signal travelled time from the satellite to the receiver, with further calculation of distance, called a pseudo-range, because it is not a direct measurement of distance but a measurement derived from time.

Assume three satellites A, B, and C. The receiver first computes the distance from the receiver to satellite A (note, that the distance from A is on a circle that falls on a wide range of locations on earth). Then the receiver calculates the distance to another satellite B, which is defined along another circle. It is evident, that the two circles intersect at two points - one of those is the exact location, but we don't know which until we get a third satellite measurement. The distance from satellite C intersects with the other circles at only one point - that is the location of the receiver (figure 1.6). Using readings from the fourth satellite, the fourth intersection point is obtained, that enables to determine the aircraft altitude [5].

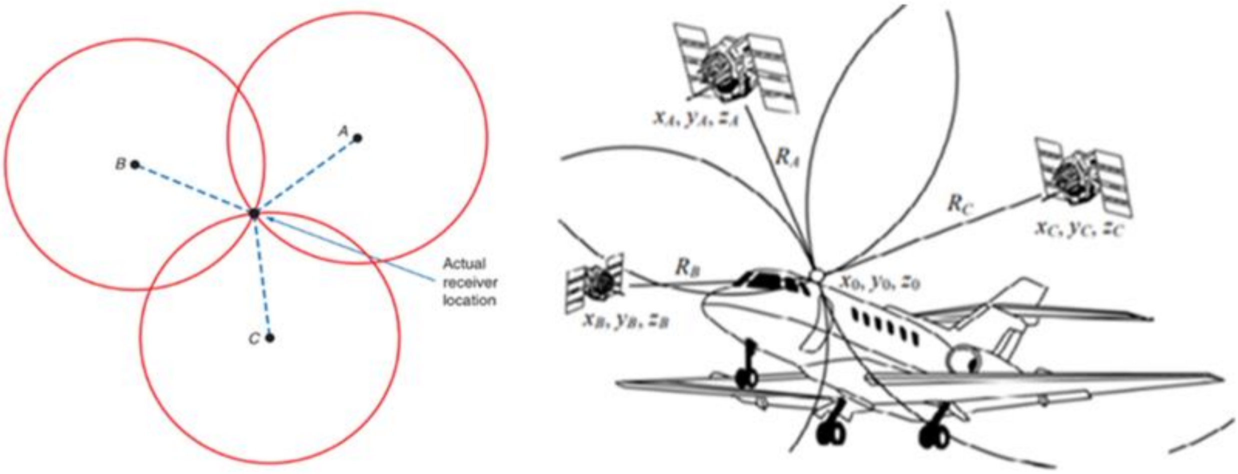

Fig. 1.6 Principle of the aircraft position determination by GNSS

The user's coordinates are determined by solving the following the system of equations:

$$\begin{cases} R_A^2 = (x_0 - x_A)^2 + (y_0 - y_A)^2 + (z_0 - z_A)^2 \\ R_B^2 = (x_0 - x_B)^2 + (y_0 - y_B)^2 + (z_0 - z_B)^2 \\ R_C^2 = (x_0 - x_C)^2 + (y_0 - y_C)^2 + (z_0 - z_C)^2 \end{cases}$$

GNSSs are widely used systems on-board the modern aircrafts due to the row of its advantages: high accuracy, possibility to work in almost all regions of the earth and near-

Earth space (ensures global coverage, and provides reliable operation even in the most remote regions); can operate in all weather conditions.

At the same time, there are a number of factors that limit the use of GNSSs: ionospheric error, which lies in fact that this area of atmosphere is loaded with electrons radiation that can "bend" and reflect transmitted radio waves; position drift – minor error in satellite position determination become much bigger when it used for receiver position calculation on Earth; timing drift – minor timing errors in satellite clock accuracy are much larger on Earth (for example, every microsecond of clock error represents a range of 300 meters); signal replication or multipath error occurs due to reflection of signals from objects such as buildings and terrain; signal propagation delay – lower atmosphere, which is much denser than other layers and can refract transmitted from satellite radio waves [6,7].

Recently, several services have emerged to improve the accuracy of GNSS, which by its nature has an accuracy of less than 10 meters. However, for many users, this level of accuracy is insufficient. One such improved service is called the Differential GPS System (DGPS). DGPS works by using a station with a precisely known location that continuously monitors all GPS satellites. By comparing their current position data with the required position, it detects any positioning errors and transmits this information to the GPS receiver. This allows the received data to be updated to provide a more accurate location. The error signals are transmitted on a separate radio frequency, so GPS receivers must also have a DGPS receiver to receive the data to correct the errors.

Another advanced GPS system is known as the Wide Area Augmentation System (WAAS). It consists of approximately 25 ground stations scattered throughout the United States, each with a precisely known location. In addition, there are two coastal stations responsible for collecting data from the other stations. This data is used to detect and correct all errors, after which differential correction signals are transmitted to a communications satellite. The satellite, in turn, transmits the correction signals to WAAS-enabled GPS receivers. The introduction of WAAS significantly improves accuracy, reducing the overall error to less than 3 feet.

But the most important problem is not yet solved, this technology cannot be used in areas with unstable satellite direction finding and in areas with the possibility of intentional or accidental jamming of the satellite radio signals.

1.4 Celestial aids of navigation

Modern celestial navigation aids can determine the aircraft heading and its coordinates. Celestial navigation methods are based on determining the position of known celestial objects relative to a chosen coordinate system. Despite, the countless number of celestial bodies, in navigation only 63 of them are used: Sun, Moon, Venus, Jupiter, Saturn, Mars and 57 stars [8].

The position of the celestial bodies is determined by special longitude and latitude. An auxiliary celestial sphere, which rotates around the Earth is introduced, it is assumed that all the bodies are located on this sphere. The celestial equator and poles correspond to the earth's equator and poles as their projections on this sphere. This system allows to accurately determine the position of celestial objects.

In the celestial sphere, latitude is called north or south declination, it reflects how far aт object is located from the celestial equator. Celestial longitude is expressed in terms of the stellar time angle, Greenwich hour angle, or the local hour angle of the luminary. These concepts allow to determine how far away from the Greenwich Meridian or another point on the celestial sphere a given object is located. The stellar time angle of a celestial body is measured from this zero celestial meridian in the direction of declination and is expressed in range of 0 to 360°. In celestial navigation, the zero reference point is the celestial meridian that passes through the vernal equinox, also known as the first point of Aries [9].

Celestial navigation aids are divided into two groups: astrocompasses and astronomical navigation systems (astroorientators).

Celestial navigation aids are divided into two groups: astrocompasses and astronomical navigation systems (astroorientators).

Astrocompasses are used to determine the true heading of an aircraft, provide flight by orthodromy. Depending on the principle of operation, they are divided into optical and radio direction finding devices. The optical devices are usually manual, but there are also automatic ones, which are equipped with photo-tracking systems. Radio direction finding automatic astrocompasses use radio radiation of celestial bodies. They differ from optical astrocompasses in that they do not depend on weather conditions.

Each astrocompass includes the following components: direction finder - for determining the direction to the centre of a celestial body; a counting and calculation device, which calculates the azimuth of the body and determines the true or orthodromic heading; aircraft and celestial body location coordinates setter; clock mechanism - to take into account the Earth's rotation and an indication device.

In an astrocompass, the true heading ψ (figure 1.7) is determined by the following formula:

$$\psi = A - \beta$$

β – is heading, the angle between the horizontal projections of the longitudinal axis of the aircraft and the direction to the celestial body, measured by a direction finder astrocompass; A - azimuth of this body, analytically determined in microprocessor-based astrocompasses.

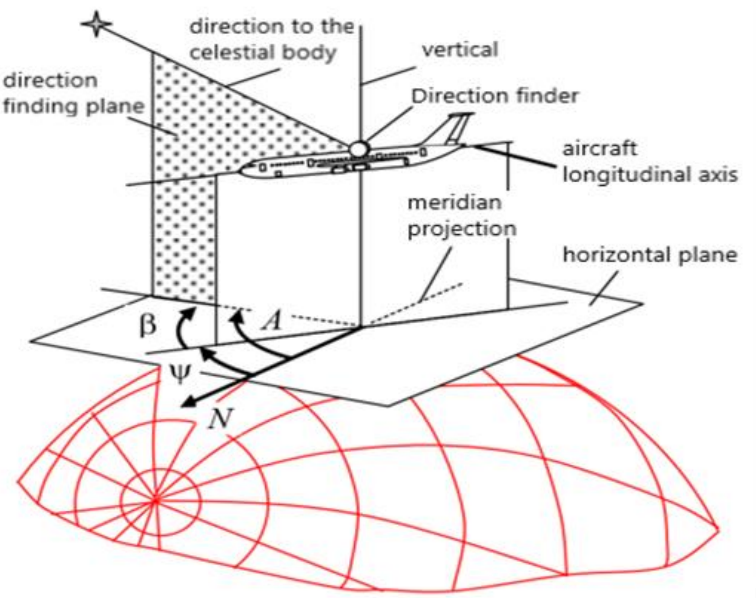

Fig. 1.7 Principle of astrocompass heading determination

The main aircraft motions that need to be compensated for to ensure accurate heading reference are:

- changes in the aircraft's angular orientation (roll and pitch) are movements that occur around the roll and pitch axes;

- the daily rotation of the Earth, which leads to changes in the time angle and horizontal coordinates of the luminary.
- the movement of the aircraft around the center of the Earth, which leads to changes in the geographical coordinates of the aircraft location and the horizontal coordinates of the luminary;

Process of celestial navigation nowadays can be automated with the help of astronavigation systems, which are commonly referred as astroorientators. The height of the celestial body is measured using a special device, called sextant, which allows to accurately determine the angle between the horizon and the observed body, automatically bear the celestial body. Bearing is a process of tracking a line directed from the observation point to the body, called line of sight; or the process of tracking the plane on which it is located, in this case, the vertical plane of the celestial body or its declination plane is usually tracked. The geographical coordinates of an aircraft location can be determined by measuring the heights of two bodies above the horizon.

As all other, celestial navigation systems have methodological errors that occur due to inaccuracies in measuring the altitude and declination of celestial bodies, which is often associated with optical distortions. In addition, errors can occur due to inaccuracies in entering the coordinates of the aircraft and celestial bodies in the chosen coordinate system. There is also an error, linked with time calculation and fluctuations in the direction finder.

The primary advantage of celestial navigation systems is their complete autonomy, so they are independent from any ground based or space equipment. Consequently, they can be utilized on routes of any length and for flights to any destination worldwide. Errors in determining the direction of flight and its coordinates are largely unaffected by the duration of the flight. But astronomical aids of navigation are almost not used on modern aircrafts due to its the most important drawback, which lies in the difficulty of obtaining and processing of navigation information.

1.5 Survey and comparative navigation method

The essence of survey and comparative navigation method lies in determination of the location of an object by comparing the area, which is depicted on the map or stored in the computer memory of the navigation system, with its actual observed view. In this case, if the image of the terrain on the map coincides with observed one, then the location of the object is considered to be recognized and aircraft coordinates are determined. But the image of the terrain or even some area contains a really huge amount of information, which during the procession increases the time of making a decision about determination of aircraft coordinates. That`s why, modern survey-comparative navigation systems do not compare the whole image area, but only some the most distinct objects, which are called ground reference points. Thus, the realization of such navigation method is simplified to performing a task of reference points (ground or astronomical) recognition in comparison with their standard location. Technical vision equipment is sensors in automatic survey and comparative navigation systems. Such sensors provide at the output the information flows, which represent the realization of random functions. So, such automatic systems use correlations between realizations of random functions, finding the extremum (maximal function value) of the correlation function to determine the navigation parameters: coordinates, angular orientation, reflective characteristics, etc. Extremum coincides with the most likely location of the object on the map. Therefore, according to the method of information processing they are often called - correlation-extreme navigation systems.

There are some disadvantages and restrictions in using such method of navigation. First of all, it can be influenced by some interfaces: cloud cover, fog, insufficient illumination can sufficiently decrease the effectiveness of survey – comparison navigation. Moreover, during flights over landmarkless area (oceans or deserts) this method is also can be used limitedly.

At the same time, survey - comparative method has a lot of important advantages:

- there are no accumulated errors and the influence of interference is reduced in comparison with other navigation methods;
- there is no need for any ground radio stations or space equipment;
- high measurement accuracy, as well as high level of navigation information redundancy;
- the ability to make measurements in any part of the Earth and near-Earth space;
- the ability of usage of automatic navigation means.

The main task of modern navigation is accurate determination of aircraft coordinates. Due to some imperfections of listed above systems, arises a problem of implementation an additional navigation system that could ensure greater flight safety and satisfy the modern tendencies of flight safety, by creating redundancy of navigation information.

Taking into account the current stage of technological progress, nowadays it is the most expediently to use the automated survey-comparative navigation systems for creation of necessary redundancy of navigation information. Such a system is fully autonomous and will be able to fully replace the satellite navigation system in places where their use is limited and will provide information for continuous correction of the INS readings, which makes it advisable for installation on both passenger aircrafts and UAVs.

CHAPTER 2

ANALYSIS OF SURVEY-COMPARATIVE NAVIGATION SYSTEMS AND SENSOR TYPES USED IN THEIR CONSTRUCTION

2.1 Basic concepts about modern survey-comparative navigation systems

As it was stated previous, the basic principle of operation of survey-comparative navigation systems (SCNS) lies in continuous observation of the ground surface and comparing obtained information with some reference information, depicted on the map or in automatic modern system contained in its memory. It is evident, that images of the ground surface contain a really huge amount of information and it is unreal to quickly process it, the rime of aircraft location determination increase. Therefore, only some the so-called reference points, which coordinates are known are observed and compared. Thar's why, the navigational content of survey and comparison measurement methods is determined by the types of such points or landmarks and their number. In such a system, the physical parameters of a landmark, such as area, geometric shape, radiation spectrum, etc., stored in the system's memory, are compared with the parameters that have been measured, and on this basis, the landmark is recognized. If the ground reference point is identified, the navigation parameters of its coordinate vector relative to the aircraft in the horizontal coordinate system are determined, which gives the possibility to easily determined the aircraft position. Additionally, to the on-route navigation and correction of INS systems, SCNSs can be used for precious short-range observation required for such stages of flight as: takeoff, landing or maneuvering near the runway or during flights along a given trajectory.

Modern SCNSs are automated systems with a continuous flow of information about reference points and use several landmarks simultaneously. In the memory of such systems, there is information not only about the physical parameters of landmarks, but also about the coordinates of their relative positions. The advantage of this approach is a significant amount of navigation information, which makes them more accurate as they are less dependent from the loss of part of the navigation data.

The inevitable elements of the SCNS (Fig. 2.1) are: sensor of the current (SCTM) and reference (SRTM) maps of the terrain, as well as the current terrain map generator (GCTM).

Usually, it performs time sampling, level quantisation and scaling by the velocity V and height H of the CTM signals. The information required for this transformation comes from the inertial system INS and radio altimeter RA. The comparing device (CD), compares information from GCTM and SRTM and searches through the possible positions of the aircraft on the reference map and for each such position calculates the correlation function of the observed image and the reference image of the terrain. The coincidences on these maps will be expressed in the form of extremums (maximum correlation function values). The solution making device, compares the results with the information about aircraft location of the aircraft from the certain path calculation system and determines the aircraft position.

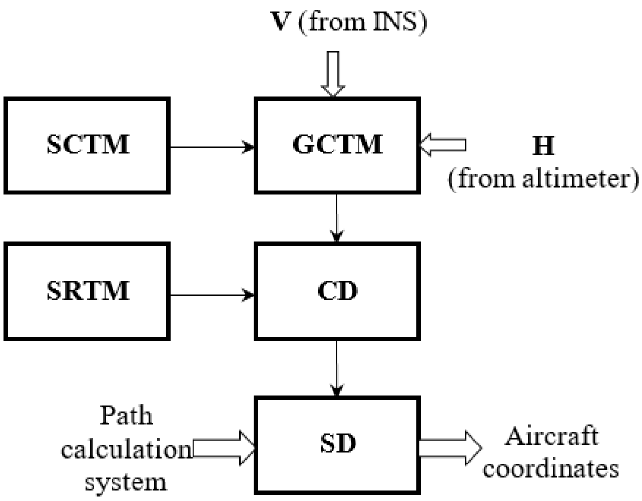

Fig. 2.1 Scheme of SCNS operation

2.2 Classification of survey-comparative navigation systems

Survey and comparative navigation systems are classified by the following features:

- depending on the physical nature of the measured signals - optical, infrared, magnetometric, gravimetric, radar, radio-technical and radiation;

- depending on the degree of sensor activity: passive (those that use direct signals of reference points and have on-board the aircraft only the receiver) and active (obtaining images of the Earth's surface by irradiating them and receiving reflected signals);

- by the autonomy nature: autonomous (based on the use of natural reference points) and non-autonomous (based on the use of artificial ground or celestial ones);

- by the level of automation: visual (non-automatic), semi-automatic, automatic.

- depending on the number of simultaneous references measurement: single one, multi-point, with a continuous flow of reference points.

According to the method of processing the initial information, there are two main types of survey comparative navigation systems, they are: terrain navigation systems and terrain map navigation systems.

In terrain navigation systems, the map is a function of a single coordinate and represents a linear image. At the same time, each terrain area has its own unique character of changes in the height or elevation of individual elements (landmarks) of these areas. The altitude, in this case, is calculated from some reference, initial level, such as the level of the world ocean, and the altimeter measures the profile relative to a point below the aircraft. Signal about the altitude is fed to the calculation machine, whose software generates a terrain map, selects a reference map corresponding to the correction area, and performs correlation processing of the generated maps. The system is the most effective at low altitudes, and is ineffective in areas with uneven terrain. Modern SCNSs are terrain map navigation systems, as the current and reference terrain maps are two or even three dimensional.

2.3 Astronomical SCNS

The so-called astronomical observing systems (AOS) are used to determine the angular orientation and location coordinates of an aircraft by analysing certain areas of the stellar sky and the characteristics of stars. Observing of a three stars (their relative position and brightness) is enough to identify a region of the sky without any mistakes.

Principle of system operation includes the following basic steps:

1. Observation: the system uses special sensors (one- or two-dimensional mosaic detectors, photoelectric sensors) to capture areas of the stellar sky;

2. Star detection: using special calculation machines and some image processing algorithms the system automatically detects stars on the obtained images.

3. Analysis: analyses the characteristics of the stars, such as their brightness, mutual coordinates and other parameters.

4. Determining the aircraft location: based on the analysis, the system determines the angular orientation and coordinates of the aircraft in space.

Astronomical SCNSs have the following advantages: independence from ground based equipment, so any access to ground points is required, making this system very useful in remote or inaccessible areas of the globe. Of course, there are also some important disadvantages of such systems, they are: systems can be complex to develop and operate, and require large computing resources to process large amounts of data in relatively small period of time.

The main problem of system realization in practice is to ensure invariance to the angular orientation of the stellar sky images, that means that the system will be able to work effectively regardless of the position or angular orientation in which the star images are captured. This means that the system can recognise and analyse the sky regardless of whether the image is upside down, rotated, or in a different position. This is achieved through the careful development of image processing algorithms and computational methods that take into account possible changes in the position of the stellar sky. For this purpose, digital information processing, larger matrix screens of sensitive elements, and microelectronic computing equipment with a high level of integration are also used.

On the altitudes of 12 kilometers or during cloudy weather, astronomical navigation systems, which rely on celestial bodies observations cannot be used. The reason behind this is that at such heights, atmospheric conditions can obstruct visibility of celestial bodies, making accurate celestial navigation impossible. Similarly, cloudy weather obscures the sky, preventing the necessary observations for celestial navigation.

2.4 Correlation-extreme SCNS

The correlation-extreme navigation system is based on geophysical fields with a random structure, the parameters of which are closely related to certain areas of the Earth's surface. Such field have the peculiarity due to the presence of certain anomalies or field characteristics that are random functions of time and space. Navigation is performed by comparing the current field image with a reference field for which a map is known. The main criterion for comparison is the correlation function, the maximum value or extremum of which coincides with the most probable location of the object on the map.

The process of location determination involves comparing the current field distribution with a reference distribution of the same field, which is intricately linked to the terrain with high precision. Given that the distributions of the current and reference fields along the route are stochastic processes, their similarity can be gauged by the mutual correlation function. The peak (extremum) of this function signifies that the current manifestation of the field aligns with a specific segment of the reference map for that field, the coordinates of which are precisely known [10].

It is also worth mention about the so-called integrated survey and comparison navigation systems, which integrate several observation and comparison systems simultaneously on board the aircraft. The information in such systems is obtained from several different survey and comparative systems. Such a system is more accurate, as it combines the advantages of several SCNSs, but the amount of information to be processed simultaneously also increases. The requirements to calculation equipment and number of additional equipment increase in turn, which makes such a system difficult to implement on board an aircraft.

All modern survey-comparative navigation systems are implemented on the correlation-extreme method of information processing. Where, primary sensors produce data streams at their output, which are manifestations of random functions. Consequently, automatic systems leverage correlations among these manifestations, seeking the extremum of the correlation function to ascertain navigation parameters.

By the type of used sensor SCNSs are divided into: optical (television, infrared, laser); radar.

2.4.1 Television sensor type SCNS

Systems with television sensors detect features based on the difference in luminance between the object and the surrounding environment. Basically, it is constructed of: a transmitting television camera and a video receiver. Most aviation television systems use transmitting tubes, the operation of which is based on the principle of external (orthicons) or internal (vidicons) photoelectric effect, which results in the formation of a potential relief on the sensitive plates corresponding to the illumination level of the projected image.

The video receiving device, after amplification, filtering and detection, synchronously scans the received signal and reproduces the transmitted image on the indication device.

2.4.2 Infrared type SCNS

Infrared equipment plays a key role in a variety of nowadays technologies and applications, including navigation systems. They are based on the use of infrared radiation, which is electromagnetic radiation with a longer wavelength than visible light and can detect the heat radiation of bodies. Infrared energy radiation corresponds to wavelengths of 700...300000 nm and is located in the part of the spectrum invisible to the human eye.

The principle of operation of infrared navigation systems is based on use of infrared radiation or thermal radiation of bodies, as all objects that have a temperature above absolute zero (-273.15°C) emit infrared radiation.

There are two methods of detecting reference points using infrared radiation: passive and active. When using the active method, the ground surface or a landmark is irradiated by an infrared projector installed in the fuselage of the aircraft. And the radiation reflected from the surface of the Earth or a landmark is picked up by on-board receiver. The passive method is based on the use of radiation emitted by the landmark itself. Infrared radiation can be detected and measured using infrared sensors and cameras. Infrared sensors can only provide information if there is a difference in thermal contrast between the object and the background. Infrared cameras with photoelectric sensing elements respond directly to individual quanta of infrared radiation and have selective sensitivity to radiation of different wavelengths.

2.4.3 Radar sensor type SCNS

The physical basis for determining the location of objects lies in the fact that in atmosphere, radio waves propagate in a straight line and at a constant speed $c \approx 3 \times 10^8$ m/s.

Generally, there are two types of radar: passive and active. Passive radar is based on the reception of an object's own radiation, in this case, only the receiver is located onboard the aircraft. These objects can be: astronomical (celestial bodies such as the Sun or stars), airborne and ground-based reference points, that emit electromagnetic waves in a wide range, including ultrasound. To detect objects in the ultrasonic wave spectrum, devices called radiometers are used.

Active radars emit own pulse signals and receives their reflections. Active radar operates by exploiting the phenomenon of radio wave reflection or scattering when encountering an object with electrical properties differing from those of the surrounding medium. When electromagnetic waves encounter such an object, they induce a secondary electromagnetic field through reflection, which can be detected by the radar system. This provides information about the presence, location, and properties of such objects.

The strength of the reflected signal depends on several factors:

1. The position of the object relative to the source of the probing signal, affecting the angle at which radar waves interact with the object.
2. The characteristics of the object, including its size, shape, and electrical properties, which influence its effectiveness in reflecting or scattering radio waves.
3. The intensity of the primary electromagnetic field emitted by the radar system toward the object.
4. The polarization state of the primary electromagnetic field, impacting its interaction with the object and subsequent reflection.
5. The wavelength (λ) of the radar waves, which influences the object's interaction with them and the characteristics of the reflected signal. Radio SCNSs use radio waves with a length of 1...3 cm (near 10 GHz), because the Earth's atmosphere is completely transparent for waves of this length. If the waves are shorter, they will be significantly absorbed by oxygen and water vapor molecules. When using long-wave radio emissions, a huge dimension antennas must be installed on the aircraft.

In radar sensor type navigation systems, image extraction is based on processing signals reflected from radio-contrast objects. This property makes it possible to determine the direction to the emitted, by the aircraft transmitter, object and the distance travelled by the signal by measuring the propagation time between the emitted and the received signals. In more simple words, the active method of such systems is based on irradiating the Earth's surface with radio waves and receiving signals reflected from the surface to form images of the Earth's surface.

The main characteristics of radar reference points are reflectivity, statistical parameters such as geometric parameters and fluctuation spectra amplitude and phase front of the reflected signal.

According to the nature of surface monitoring, the radars can be divided into the following types:

- circular visibility radars, which are capable of scanning the environment 360 degrees around the aircraft.

- sectional visibility radars are limited in their ability to scan only limited sectors of ground surface. They can be targeted at specific directions or sectors of surface that meet the requirements of a particular mission or task.

- programmable scanning radars can scan a space according to predefined programmes. They can automatically move from one direction to another or scan specific areas in a specific sequence.

- side-view radars are aimed at lateral directions relative to the aircraft. They provide the ability to detect objects or targets that are not in the direct line of flight of the aircraft.

Each of these types of radars has its own advantages and applications depending on the specific flight performance and customer requirements. But in the radar survey-comparative navigation systems the most used are circular visibility radars. They provide a complete view of the space around the aircraft without directional restrictions. Such radars are also known as panoramic radars, they send signals in the form of short-term pulses from the aircraft towards the Earth, providing an image of the earth's surface in the form of a circle, with the aircraft's projection on the ground in the centre, allowing the pilot to clearly see aircraft position in relation to the environment. These systems allow pilots to obtain full 360-degree images of the earth's surface in real time, which is essential for navigation and flight safety. Radar emits sensing pulses using an antenna that has a narrow direction in the horizontal plane and a wide direction in the vertical plane. This antenna has a rotational radiation pattern in azimuth, which results in the irradiated narrow strip of ground surface, describes a circle with a maximal radius R_{Max} (Fig. 2.2). It is necessary to emit several sensing pulses by the time the antenna turns to an angle θ, which is equal to the width of the antenna directional pattern. This helps to locate objects around the aircraft, detect potential threats and control the flight during piloting [11].

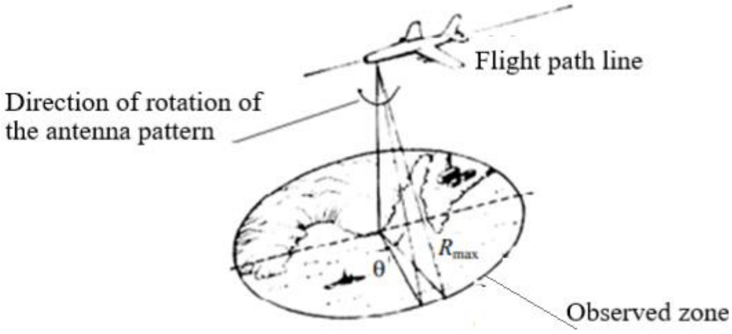

Fig. 2.2 Principle of circular radar image formation

The practical accuracy of the aircraft's location determination using panoramic radars in survey comparative navigation is about a hundred meters.

2.4.4 Laser sensor type SCNS

A laser - is an optical device that generates intense and monochromatic light that can be directed into extremely thin beams. A laser, functions as an oscillator operating within the optical frequency range. This range spans from the far infrared to the vacuum ultraviolet (VUV) or soft X-ray regions. Monochromatic property allows lasers to perform a variety of tasks, one of which is the precise distance measurement. Monochromatic characteristic of the lasers allows them to have high resolution and precision, making them indispensable in measurement tools, medicine and material processing [12].

With the use of laser sensors, it is possible to create laser location systems that extract features based on the construction of two-dimensional (2D) and three-dimensional (3D) images of objects. An analysis of advancements in three-dimensional image formation and the development of automated recognition devices reveals that laser systems are the most promising technology for purpose of creation of automatic and autonomous navigation survey – comparative navigation systems. The most promising are laser systems for forming three-dimensional images, based on the LiDAR technology, which have high spatial and temporal characteristics. LiDAR is an active type distance measuring locator, which allows to implement the method of laser stereometry, which is a direct method of measuring the three-dimensional shape and size of the observed object.

LiDAR, originating from the English abbreviation Light Identification, Detection, and Ranging, is a technology utilized for gathering and analyzing data regarding distant objects. It uses active optical systems, which harness the phenomena of light reflection and scattering within transparent and translucent media.

LiDAR, an active remote sensing technique, can be utilized across spaceborne, airborne, and ground-based platforms. Spaceborne LiDAR refers to LiDAR systems positioned on satellites. These systems employ robust lasers and exceptionally sensitive receivers to gather intricate three-dimensional data regarding Earth's surface, atmosphere, and other elements from space. Spaceborne LiDAR plays a crucial role in monitoring alterations in Earth's surface, encompassing aspects like land cover, vegetation, topography, and ice sheets, providing comprehensive global coverage. Ground-based LiDAR systems are stationary devices typically mounted on tripods or other platforms on the Earth's surface. They emit laser pulses in a horizontal or vertical scanning pattern to collect detailed three-dimensional data of the surrounding environment.

Airborne LiDAR systems are installed on aircrafts or UAVs to collect high-resolution topographic data over specific areas of interest. These systems emit laser pulses towards the ground surface and measure the time it takes for the light to return to the sensor after reflecting off the target. Airborne LiDAR is commonly used for mapping terrain, forest inventory, urban planning, floodplain mapping, and archaeological surveys. An airborne LiDAR survey – comparative navigation system typically comprises two main components: a range finder with laser sensor for detecting ranges and a positioning and orientation system for measuring the orientation of the sensor. Together, these components enable the derivation of three-dimensional (3D) image of detected objects (figure 2.3).

Fig. 2.3 Airborne LiDAR image

2.5 Comparison of SCNSs sensors and determination of the most appropriate for use on a modern aircraft

There are various survey-comparative systems, each of them has its advantages and limitations, mainly concerned with the primary sensor type. Let's determine the most advanced system according to the table 2.1.

Table 2.1

Types of system sensors and their main characteristics

№	System sensor type	Output data format	Useful characteristics	Advantages	Limitations
1	Laser locator (LiDAR)	3D image	Size; 3D shape; location of objects; spatial distribution of surface areas.	- able to form 3D images; - have high resolution; - provides a large amount of initial information; - has enough distance range. - operate all day long.	-measurement accuracy depends on the transparency of the atmosphere
2	Infrared	2D infrared image	Shape; max/min emission; number and location of hot spots.	- operate all day long; - information from these sensors is the easiest to extract.	- have a high inertia; - limited in distance; - accuracy depends on weather conditions.
3	Television	2D semitone image	Shape, size, texture internal structure o objects.	- provides a large amount of initial information; - have high resolution;	- can normally operate only if the object is optically visible.
4	Microwave radar	2D image; Doppler modulation	Speed and pulsation of the frequency; beam width; size, number and location of objects.	- operate all day long, almost in any weather conditions; - have the largest distance of effective use.	- have limited resolution over long distances.

Television and laser systems can give the largest amount of information among other systems. But despite of this, television sensors has some major disadvantages: technical complexity, high sensitivity to interferences. Moreover, they can only work properly if the landmarks are optically visible and have the sufficient light illumination.

Infrared sensors operate by detecting variations in thermal contrast between the object being irradiated and its surrounding environment, that`s why, fog and rainy clouds greatly limit the effectiveness of their use. Moreover, a wrong source of radiation can cause a significant deviation of the aircraft from the desired trajectory of movement. It is important to note, that such systems are also limited in the distance of use.

Radar sensors offer a wide range of applications as they can detect reference points and extract their features over long distances, even in difficult conditions such as bad weather. However, they have limited accuracy in determining the geometric characteristics of objects, so radar systems can detect objects but cannot identify them. As a result, the received information may not be sufficient for automatic object recognition. In some cases, radar systems can detect objects but cannot identify them, which can lead to false observations or the need for additional confirmation Additionally, they can be subject to electronic interference, such as signal interception or active jamming, which can lead to signal distortion or loss.

Unlike imaging techniques that project the 3D world into a two-dimensional image space and may suffer from geometric distortion like relief displacement, LiDAR directly measures the geographic environment in 3D. Therefore, users do not need to address georeferencing issues, which are often challenging in image processing. This aspect stands out as one of the primary advantages of LiDAR. Unlike optical or radar imagery, airborne LiDAR data don't provide continuous measurements or mapping of the Earth's surface. Instead, each laser pulse and its returns represent samples of the environment, even when the point density is very high. Interpolation becomes necessary to create spatially continuous digital products or maps from these discrete points.

At the same time, systems, based on the LiDAR technology provides several additional key properties that enhance the efficiency of SCNSs:

- contrast independence: image quality remains unaffected by contrast values, even if the contrast is zero. Changes in the background environment do not impact image quality as well;

- images obtained via LiDAR include metric data regarding the three-dimensional shape and size of observed objects. These metrics serve as primary features for object recognition;

- the LiDAR system is characterized by having a sufficiently long range, allowing for the capture of data across extensive distances.

- the system is completely autonomous and all necessary equipment is based onboard the aircraft;

- system can provide the accurate information both at the daytime or at night time.

Comparative analysis indicates: despite the fact that LiDAR navigation system depends on the atmosphere transparency, due to the row of important advantages, such system is the most prospective in implementation in comparison to other sensors.

2.6 LiDAR based three-dimensional ground reference points image formation system

In an automatic navigation system pulse LiDAR is used. It assesses the duration of a laser beam's propagation to the object and backward. Using the speed of light value, the system calculates the distance to the object. This operation is instantaneous, making it easy to collect accurate data on the location and movement of objects in space.

The optical system of the system transmitter consists of: a laser source, an optical lens, a polarising light beam splitter and a scanner.

System operates in the following way: a special device, called the pulse generator, generates a series of electrical energy pulses of necessary duration (in nanoseconds) and frequency (figure 2.4). This information is fed to the laser input, which in turn emits the laser radiation. It passes through the diffusing lens, which provides the necessary divergence of the laser beam. Then, laser radiation passes through the filter and polarising beam splitter (polarising light distributor), which separate light depending on its polarisation and is used to control the light flux and direct it onto the rotation mirror, steering the laser pulses across a specified area for remote sensing, autonomous navigation, enabling 3D mapping, imaging, or profiling (sensing radiation).

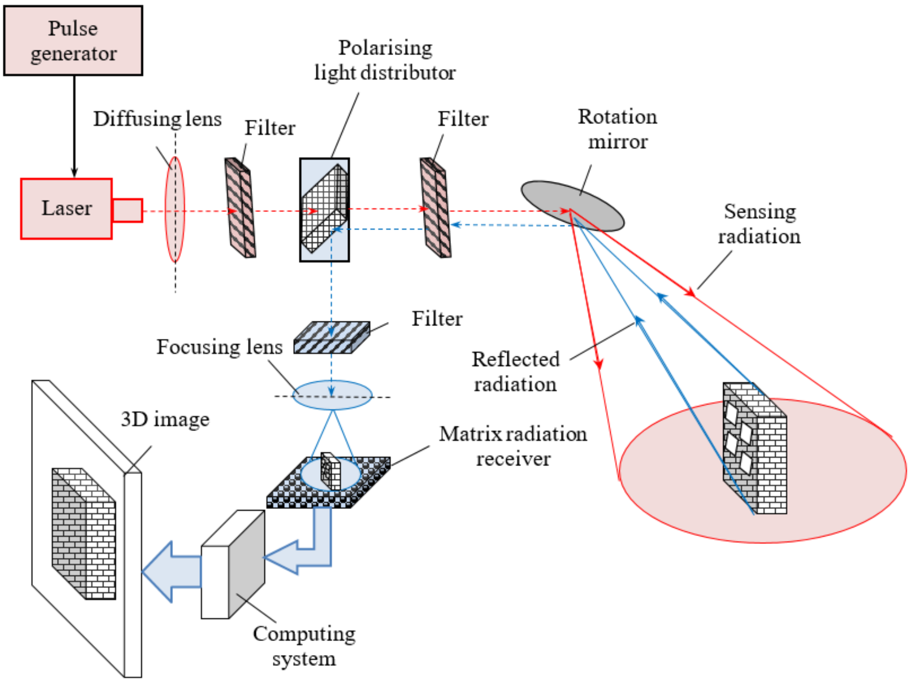

Fig. 2.4 Principle of 3D image formation by LiDAR

The scattered radiation is received by the receiver, which has the same aperture as the transmitter. The nanosecond laser impulses reflecting from the object and underlying surface, which surrounds the object, return to the mirror and goes through the filter and polarising light distributor to the focusing lens. This lens controls the direction and distribution of light and converge the laser rays, directing them to a focal point. Its function is to collect and focus light from the area in front of the receiver onto the matrix radiation receiver (MRR). In this case, a 3D image of the object is recorded in one laser pulse. The image quality in this case does not depend on vibrations, platform speed and stability of the scanning and synchronisation systems.

A three-dimensional image is displayed in the focal plane of the matrix radiation receiver. The coordinates of the object's surface are measured in polar coordinates (angle - angle - range). During pulse sensing, the position of the matrix element determines the angular coordinates of the object's surface element, and the time the pulse travels to and from the object determines the range.

The laser system for forming a three-dimensional image uses a pulsed laser to sense a remote object, and the image of the object is captured by MRR, where each matrix element records both the presence of radiation reflected by the object in the image plane and the distance to it. In this case, the presence of an object on the matrix elements makes it possible to determine two of its characteristics - length and width, and the distance contains information about the third characteristic of the object - the spatial component.

The principles of forming three-dimensional images using an impulse laser system for forming three-dimensional images (LSFTDI) is explained in figure 2.5:

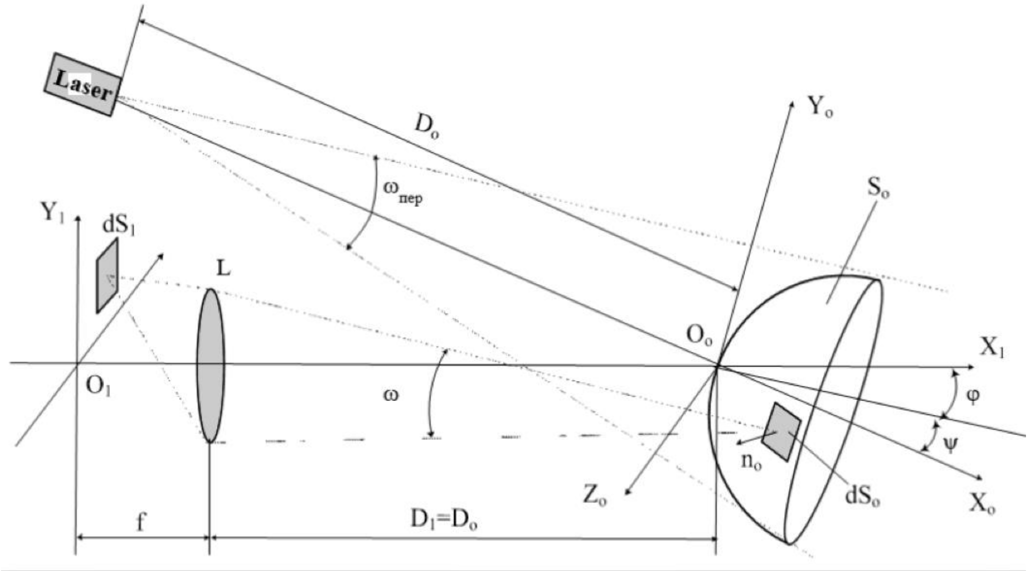

Fig. 2.5

The laser irradiates the object with laser pulses of nanosecond duration. The signal reflected from the object is focused by the optical system onto the matrix radiation receiver. The strength of the reflected radiation generated by some element of the surface dS_o with coordinates x_o, y_o, z_o can be written as follows:

$$dI_o(y_o, z_o, t) = \frac{WT_o\rho(\gamma_o)\cos^2\gamma_o\tau_{пер}}{\pi\omega_{пер}(D_o + x_o)^2}\delta\left(t - \frac{D_o}{c} - \frac{x_o(y_o, z_o)}{c}\right)dS_o \qquad (2.1)$$

where: W - is the radiation energy; T_o is the coefficient of attenuation of radiation by the atmosphere; $\rho(\gamma_o)$ is the brightness coefficient of the dS_o element; γ_o is the angle between the normal to the surface element and the sensing direction; $\tau_{пер}$ - is the coefficient of attenuation of radiation by the transmitting optics; $\omega_{пер}$ - is the angle of divergence of radiation from the sensing source; D_0 - distance from the radiation source to the plane passing through the point on the object closest to the emitter ; c - is the speed of light; t - is the time counted from the moment of pulse emission by the laser; $x_0(y_0,z_0)$ - is the distance between the surface element dS_o and the image plane.

For a monostatic system, the distance D_1 from the picture plane to the optical system is equal to the distance D_0, the angles ψ and ϑ, which characterise the orientation of the systems $O_1X_1Y_1Z_1$ and $O_0X_0Y_0Z_0$ with each other, are zero, so the light flux reflected from the surface dS_o is focused by the lens (L) on the area dS_1 of MRR can be written as:

$$dF_1(y_1,z_1,t)=\frac{S_{\text{об}}WT_0^2\cos^2\gamma_o\rho(\gamma_o)\tau_{\text{пр}}\tau_{\text{пер}}}{\pi\omega_{\text{пер}}(D_o+x_o)^2 f^2}\delta\left(t-\frac{2D_o}{c}-\frac{2x_o(y_o,z_o)}{c}\right)dy_1dz_{1,} \tag{2.2}$$

where (according to the figure 2.5): $\tau_{\text{пр}}$ - is the attenuation coefficient of the receiving optics; $S_{ob} = D_1 \cdot \omega$ - area of the lens; ω - is the angle covered by the lens L, with the vertex at dS_o.

As follows from the expression (2.2), when an object is irradiated by pulses of nanosecond duration, each elementary area on the surface of the object with coordinates x_o, y_o, z_o is focused by the lens into the focal plane region with coordinates y_1, z_1 and the time of arrival of radiation at the point of the focal plane with coordinates y_1, z_1 contains information about the third coordinate of the object - x_o.

To register information about the third coordinate of the object, it is necessary to record the time when the light flux reaches the focal plane. In accordance with the expression 2.2, the time of the laser pulse passing from the emitter to the surface element dS_o and returning to the MRR can be written as follows:

$$t=\frac{2D_o}{c}+\frac{2x_o(y_o,z_o)}{c} \tag{2.3}$$

The information about the third coordinate is contained in the component $\frac{2x_0(y_0,z_0)}{c}$ of expression (3.3). Therefore, to obtain a three-dimensional image, it is sufficient to record the time of arrival of radiation at the corresponding points of the focal plane of the lens relative to the beginning of the arrival of radiation reflected by the closest point of the object at the input of the observation system.

It can be explained in the following form (figure 2.6): the difference $\Delta R=R2-R1$ characterises the spatial component of the object and is fixed by the time interval τ due to the difference in distances to different elements of the object [13]:

$$\tau = \frac{2\Delta R}{c} \quad , \qquad (2.4)$$

where: ΔR = $x_0(y_0; z_0)$ – distance to the object with coordinates (y0; z0); c – speed of light.

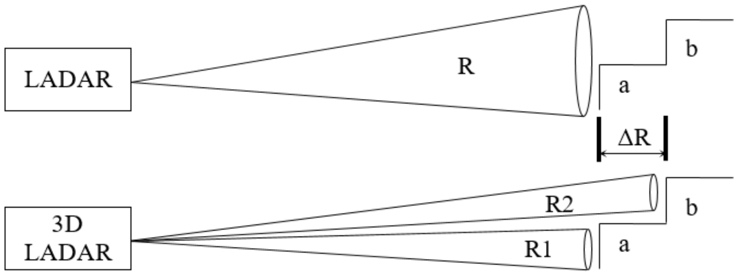

Fig. 2.6 The principle of formation of the spatial component of a 3D image

Then, the time of receiving the radiation reflected from the object according to the formula (2.4) is equal to ($R = D_0$):

$$t = \frac{2R}{c} + \frac{\Delta R}{c} \quad , \qquad (2.5)$$

In this case, the selected MRR element will record the time interval:

$$\tau = \frac{2x_0(y_0, z_0)}{c}$$

Finally, the matrix radiation receiver generates information about object flat image (records its length and width - the y_0 and z_0 coordinates). The pulse generator, counter and time intervals matrix provide measurement of the third coordinate (spatial component) for each element (dS) of the object's flat image (figure 2.7), by determining the time difference between fixing the first signal reflected from the object and the subsequent ones for each individual element of the matrix of time intervals.

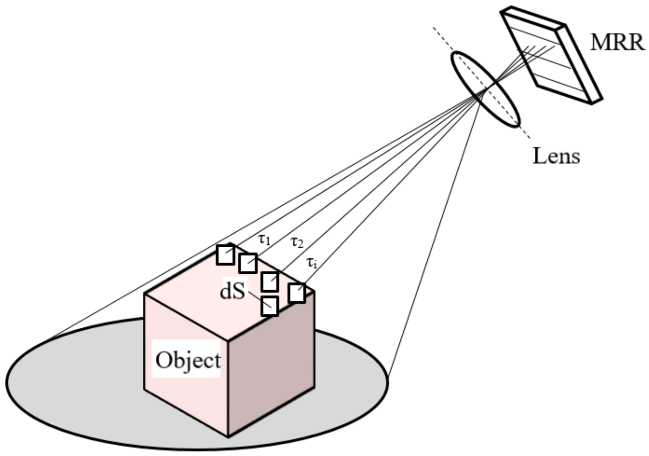

Fig. 2.7 Formation of the spatial component

Subsequently, taking into account the speed of light, the information processing unit (computing unit, figure 2.4) calculates the coordinates $x_0(y_0, z_0)$ and generates a three-dimensional image of the irradiated object in the form of a matrix in the computer memory (figure 2.8):

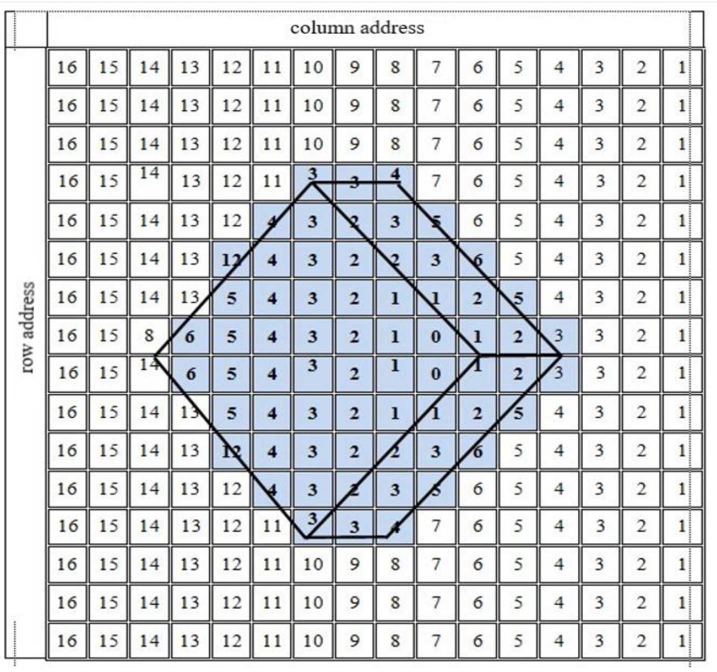

Fig. 2.8 Matrix of time intervals of a three-dimensional image of a spatial object

Based on utility criteria, the geometric properties of ground reference points, such as size (length, width and height), shape, volume, etc., are the most informative features independent of sensor type. Taking into account this information, it can be stated that the most important LiDAR based navigation system advantage - is the fact that it is only one among other SCNSs that can form the 3D images of ground reference points along the flight route.

Using of laser sensors to generate three-dimensional object images for extracting geometric features proves most suitable for efficiently obtaining maximum information in minimal time period.

The resulting 3D image can be used for automatic detection of ground reference points, their automatic recognition and further aircraft position finding with a high probability.

CHAPTER 3
RECOGNITION OF NAVIGATIONAL REFERENCE POINTS IN SURVEY AND COMPARATIVE NAVIGATION SYSTEMS

3.1 Characteristics of a geometric body

A three-dimensional image of an object contains all the information needed to recognise it. By analysing a 3D image, you can get all the same features as when processing 2D images, as well as additional characteristics of the object that arise due to its 3D nature.

Analysing the principle of operation of laser devices during the formation of three-dimensional images using a pulsed laser system, it was found that these additional features are: the volume of the parallelepiped describing the recognised object (figure 3.1 a), the volume of the object itself (fig. 3.1 b), the volume of the geometric shapes that make up the object (fig. 3.1 c), and its average height (fig. 3.1 d).

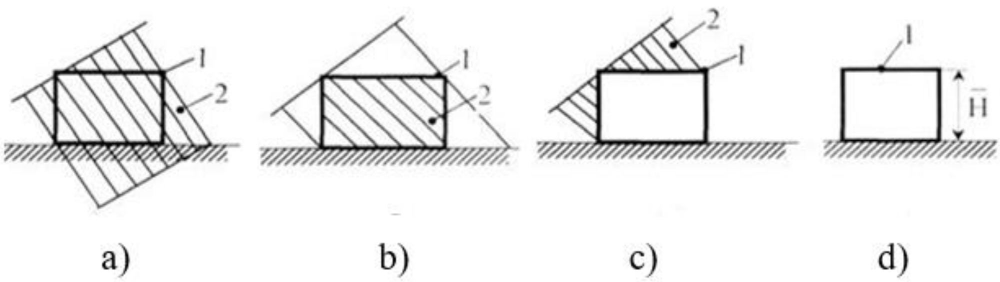

Fig. 3.1 Characteristics obtained from a three-dimensional image:

1 - object; 2 - measured volume

Volume of the object - provides the most complete characteristic of a spatial geometric shape. It can be determined by analysing a three-dimensional image using the mentioned characteristics of a geometric body.

3.2 Determining the boundaries of an object and the nature of its surface when analysing its three-dimensional image using the differential method

When an object is irradiated by a laser system, MRR forms its three-dimensional image. For the further compare of the etalon reference point image and current one, the object's boundaries and shape must be determined to determine its geometric characteristics. To do this, we can use the derivative method, which is based on the geometric value of the derivative on the plane. According to this method, the derivative (f ‘(x)) of the function (f(x)) is the angular coefficient of the tangent line to the graph of the function (y = f(x)) at the point (A (x, y)) (Fig. 3.2).

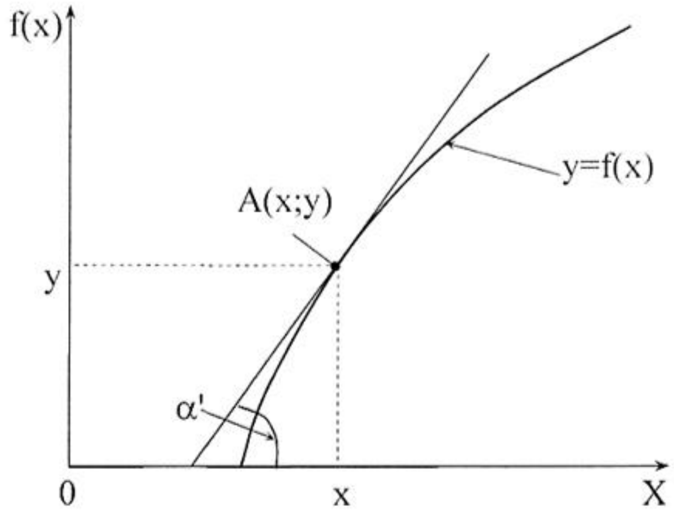

Fig. 3.2 Graphical representation of the derivative

The angular coefficient of the tangent line is expressed as the tangent of the angle between it (α') and the OX-axis. The tangent to the function f(x) is a straight line.

The equation of a line on a plane in the rectangular Cartesian coordinate system is written by the following formulas:

$$Ax + By + C=0, \tag{3.1}$$

$$\text{or} \quad y=kx+b, \tag{3.2}$$

where: $k = \frac{A}{B}$ - is the angular coefficient that characterises the angle of inclination of the line to the X-axis; ; α' - is the angle between the line and the OX-axis.

To use the method of derivatives in the processing of three-dimensional images, it is necessary to consider the intersection of a ground object with an "intersection plane" that passes through the horizontal line of the MRR elements and coincides with the range vector O (Fig. 3.3. a, 3.4. a).

It intersects an object and forms intersection lines with its surfaces. Depending on the shape of the surfaces, the intersection lines can be different:

- when intersecting planes (for example parallelepiped), the intersection lines will be straight segments (Fig. 3.3.b), which can be described by functions (3.1) and (3.2), and the differentials of these functions will be constants for each basic element of the shape (Fig. 3.5. a, b);

- at the intersection of surfaces of the second order, these lines will be second-order curves (Fig. 3.4. b), the general equation for which is written in the form:

$$a_{11}x^2+a_{12}xy+a_{13}y^2+a_{14}x+a_{15}y+a_{16}=0 \quad (3.3)$$

The differential of this function will be constantly changing (Fig. 3.5. c).

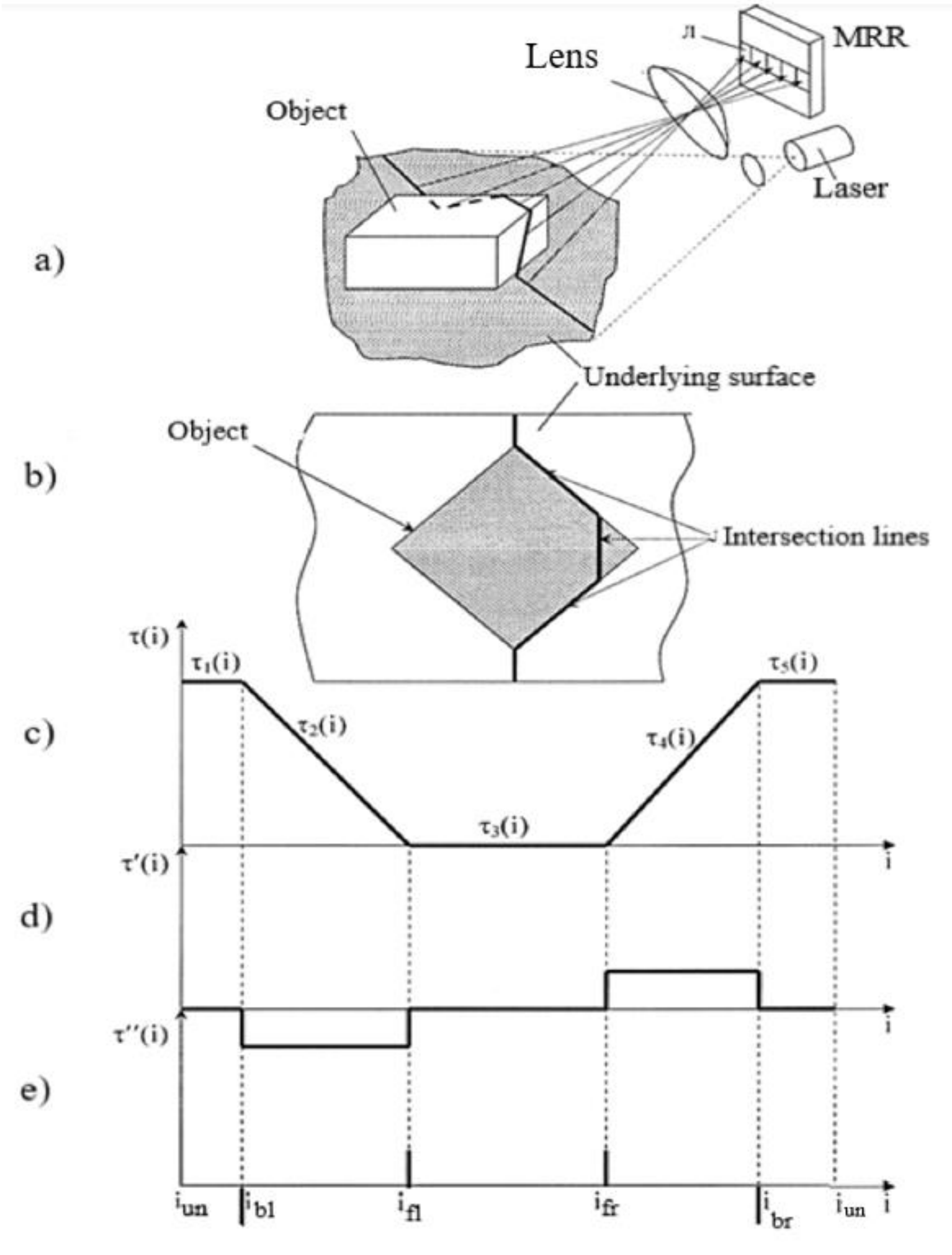

Fig. 3.3 Analysis of a three-dimensional image of a “parallelepiped object” using the differential method

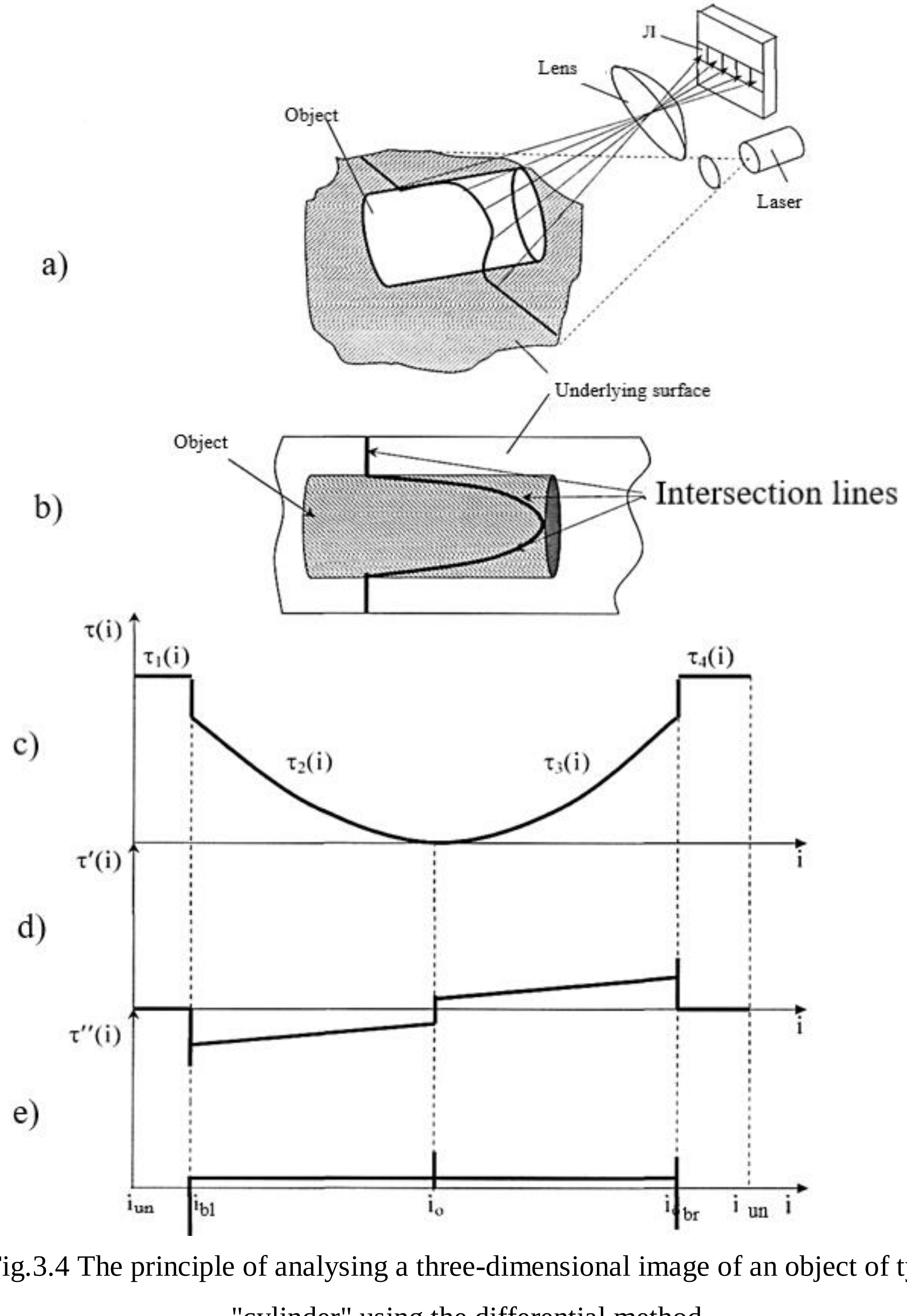

Fig.3.4 The principle of analysing a three-dimensional image of an object of type "cylinder" using the differential method

Where: i_{un} - is the number of the elements of the receiver line that record the underlying surface; i_{bl} - the number of the element that records the left boundary of the object; i_{br} - number of the element of the receiver row that records the right boundary of the object; i_{fl} - number of the element that records the left boundary of the object's foundation; i_{fr} - the number of the element that records the right boundary of the object's foundation; i_0 - the number of the MRR row element that records the point of extremum of the envelope function.

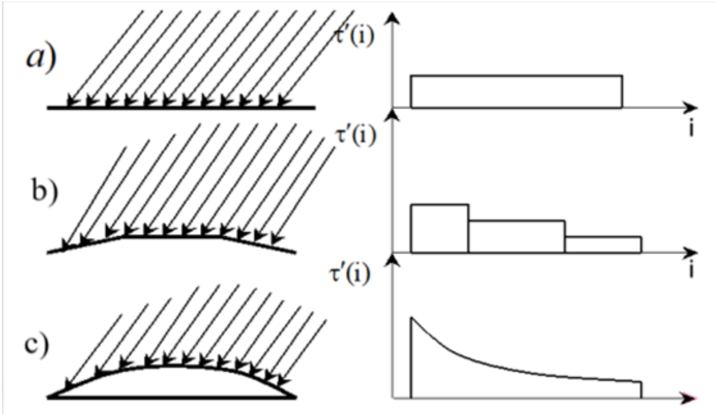

Fig. 3.5 Differential types of basic shape elements

In order to analyse the images of an object that is recorded using a MRR, it is advisable to perform image analysis sequentially, using time intervals registered by separate horizontal lines of the receiver. In this case, the elements of the horizontal line of the MRR are located on the OX-axis, and the function y=f(x) is an envelope for the time intervals τ, which are registered by the elements of the receiver horizontal lines (Fig. 3.6), and is written in the form: $\tau_n(i)=f(i)$, where $\tau_n(i)$ is the envelope function for the n-th basic element of the form (BEF); i - is the ordinal number of the element on the receiver line.

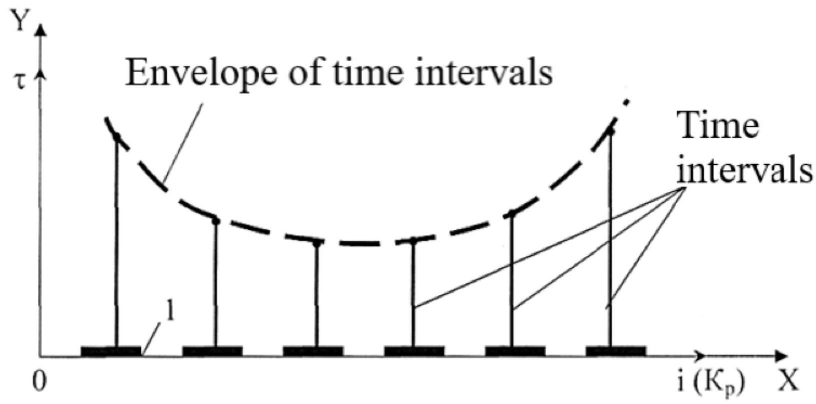

Fig. 3.6 Formation of the envelope of time intervals:

1 - the first element of the receiver line; K_p - the relative distance between the MRR elements

There are two scenarios depending on the type of irradiated surface:

Case 1: when irradiating a ground object consisting of planes (for example, parallelepiped), the time interval graph for one horizontal line of MRR will look like, figure 3.3.c. This case can be mathematically described by a system of equations:

$$\begin{cases} \tau_1(i)=k_1 i+b_1, & [i_{un};\ i_{bl}]; \\ \tau_2(i)=k_2 i+b_2, & [i_{bl};\ i_{fl}]; \\ \tau_3(i)=k_3 i+b_3, & [i_{fl};\ i_{fr}]; \\ \tau_4(i)=k_4 i+b_4, & [i_{fl};\ i_{br}]; \\ \tau_5(i)=k_5 i+b_5, & [i_{br};\ i_{un}]. \end{cases} \tag{3.4}$$

Where: k_n - is the angular coefficient of the tangent to the envelope for the n-th BEF; b_n - is the free component of the tangent line to the envelope for the n-th basic element of the irradiated form.

Each equation of system (3.4) corresponds to the intersection line created by the intersection of the intersection plane with the n-th BEF. The angular coefficient kn characterises the intersection line that coincides with the corresponding plane of the object. Therefore, the coefficients k_1 - k_5 characterise the tangents of the angles between the horizontal line of the MRR elements and the corresponding intersection line of the n-th BEF. Based on this, using the angular coefficients, i.e., the derivatives of the function, it is possible to characterise the planes that make up the irradiated object. For the described case, the derivative of the time intervals for i-th element of BEF received by each individual cell of the receiver row is written by the formula:

$$\tau'(i) = \frac{d\tau(i)}{dK_p} = k$$

Provided that all the elements of the MRR row are at the same distance from each other, i.e. dK_p = const, the main characteristic of the planes that make up the object will be the difference between the time intervals recorded by adjacent radiation receivers:

$$d\tau(i)=\tau(i+1) - \tau(i)$$

The calculation of the derivative signals on one MRR row for each individual plane (BEF), which makes up the irradiated object, can be written as follows:

$$\begin{cases} \tau'_1(i)=k_1=0, \ (\alpha'=0) \quad [i_{un}; i_{bl}]; \\ \tau'_2(i)=k_2, \quad (\alpha'\neq 0) \quad [i_{bl}; i_{fl}]; \\ \tau'_3(i)=k_3=0, \ (\alpha'=0) \quad [i_{fl}; i_{fr}]; \\ \tau'_4(i)=k_4 \quad (\alpha'\neq 0) \ [i_{fr}; i_{br}]; \\ \tau'_5(i)=k_5=0, \quad (\alpha'=0) \ [i_{br}; i_{un}]. \end{cases}$$

The graph of derived signals for the described case is shown on the figure 3.3 d.

The analysis of calculations shows that the geometric features of ground objects can be characterised by the size of the object and its shape. The jump-like change in the derivative signals on a certain row of the receiver makes it possible to identify the boundaries of the planes: for the underlying surface (i_{un}, i_{bl}) and (i_{br}, i_{un}); for the side surfaces (i_{bl}, i_{fl}) and (i_{fr}, i_{br}); for the upper base of the object (i_{fl}, i_{fr}). Knowing these boundaries, the distance to the irradiated object and the characteristics of the radiation source, the dimensions of the object can be determined.

For determining the volume of a parallelepiped, the main components are the dimensions of the base of the object or its area. Therefore, the surface area of an object (S_o), which is in the field of view of one MRR element with dimensions axb, is written as:

$$S_0 = (a + \Delta h)\cdot(b + \Delta h)\frac{D^2}{f^2} \tag{3.5}$$

Where, f - focal length of the lens. After calculation of the number of MRR elements that receive the signal from the base of the object, using formula (3.5), the area of the object's base can be found.

Selecting the boundaries of object elements can be challenging, especially when the transition from one surface element to another is not well-defined. To enhance the clarity of object surface element boundaries, we propose to analyze the time intervals using the second derivative. In the scenario depicted in fig. 3.3 e, this analysis results in transforming the boundaries of object elements into more clearly defined singular jumps. The analysis of the second derivative of the time intervals clearly identifies the elements on the MRR row that records the boundaries of the object's BEF. By determining the numbers of these elements for each row of the MRR, the total number of elements on which the object's base is projected can be found. Mathematically, this transformation can be described as follows:

$$\begin{cases} \tau''_1(i) = 0, \\ \tau''_{12}(i) = k_2\text{-}k_1, \quad [i_{bl}]; \\ \tau''_2(i) = 0, \\ \tau''_{23}(i) = k_3\text{-}k_2, \quad [i_{fl}]; \\ \tau''3(i) = 0, \\ \tau''_{34}(i) = k_4\text{-}k_3, \quad [i_{fr}]; \\ \tau''_4(i) = 0, \\ \tau''_{45}(i) = k_5\text{-}k_4, \quad [i_{br}]; \\ \tau''_5(i) = 0. \end{cases}$$

Where $\tau''_n(i)$ - is the second derivative of the envelope $\tau_n(i)$ for the i-th element of the receiver row, which records the time interval from the n-th BEF.

Thus, during analysing three-dimensional images of any object, such as a parallelepiped or a vertical cylinder, the boundaries of the objects will be determined by the extreme negative jumps of i_{bl} and i_{br} when calculating the second derivative, and the boundaries of the object's base will be determined by the internal positive jumps of i_{fl} and i_{fr}.

Case 2: if the irradiated surface is of second order, the envelope of time intervals for a single MRR row will look like a parabola (Fig. 3.4.c). Such objects that do not have a well-defined base will be characterised by their boundaries and the height of each individual element of the object surface relative to the underlying surface.

The boundaries of an object that contains a second-order surface are determined by analysing the time intervals of the receiver horizontal line using the first or second derivative.

Mathematically, the time intervals for irradiation of a second-order surface are expressed as follows:

$$\begin{cases} \tau_1(i) = k_1 i + b_1, & [i_{un};\ i_{bl}]; \\ \tau_2(i) = a_2 i^2 + b_2 i + c_2, & [i_{bl};\ i_o]; \\ \tau_3(i) = a_3 i^2 + b_3 i + c_3, & [i_o;\ i_{br}]; \\ \tau_4(i) = k_4 i + b_4, & [i_{br};\ i_{un}]. \end{cases}$$

The first derivative of the time intervals characterising the second-order surface for one row of the receiver is graphically represented in figure 3.4. d, and mathematically can be described as:

$$\begin{cases} \tau'_1(i) = k_1=0, \quad (\text{when } \alpha' = 0) & [i_{un};\ i_{bl}]; \\ \tau'_2(i) = 2a_2i+b_2, & [i_{bl};\ i_0]; \\ \tau'_3(i) = 2a_3i+b_3, & [i_0;\ i_{br}]; \\ \tau'_4(i) = k_4=0, \quad (\text{when } \alpha' = 0) & [i_{br};\ i_{un}]. \end{cases}$$

The second derivative of the time intervals characterising the second-order surface for one receiver row is graphically presented in fig. 3.4.e, and the mathematical calculations for calculating the second derivative will be as follows:

$$\begin{cases} \tau''_1(i) = 0, & [i_{un};\ i_{bl}]. \\ \tau''_{12}(i) = 2a_2i+b_2, & [i_{bl}]; \\ \tau''_2(i) = 2a_2, & [i_{bl};\ i_0] \\ \tau''_{23}(i) = 2a_3i+b_3 - 2a_2i-b_2, & [i_0]; \\ \tau''_3(i) = 2a_3, & [i_0;\ i_{br}] \\ \tau''_{34}(i) = -2a_3i-b_3, & [i_{br}] \end{cases}$$

Therefore, the boundaries of such object types as: "sphere", "semi-sphere" or "horizontal cylinder" will be determined by the extreme negative jumps of i_{bl} and i_{br}.

The shape of the objects' surfaces can be determined by analysing the calculations of the second derivative for all the elements of the MRR that have recorded the object according to the following algorithm: if the second derivative at the intervals between the jumps that record the BEF boundaries is not equal to zero $\tau''(i)\neq0$, then the second-order surface is irradiated, and when irradiating planes, the second derivative at these intervals is equal to zero $\tau''(i)=0$.

3.3 Three-dimensional ground reference points images processing using the method of derivatives

Figure 3.7 represents the cross-section of a ground reference point and the projection of one row of MRR elements onto an image plane passing through the point on the object's surface closest to the receiving optical system. Then, the distribution of time intervals $\tau_{ij}=2l_{ij}c_2$ of the reflected signal registration for each element of the MRR row relative to the beginning of the radiation arrival at the input of the observation system will be as shown in figure 3.8.

Figures 3.7 and 3.8 show that each element of the MRR contains information about the position of the corresponding projection of the irradiated object or the underlying surface, and the time of registration of the reflected signal contains information about the distance of the corresponding part of the irradiated object from the image plane (IP) passing through the point on the object surface closest to the receiving optical system.

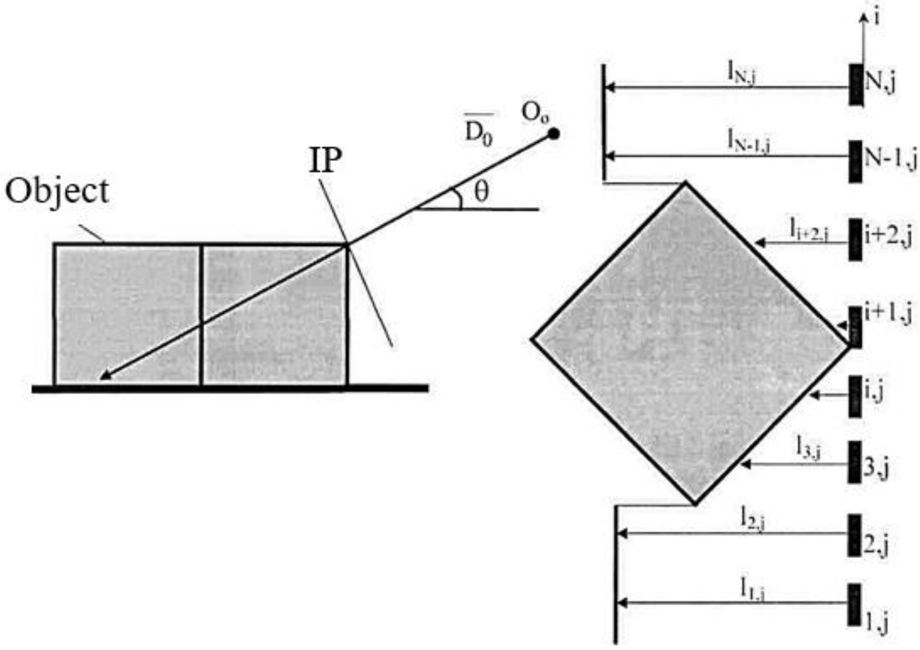

Fig. 3.7 Intersection of a ground object and projection of one horizontal line of the MRR elements on the image plane

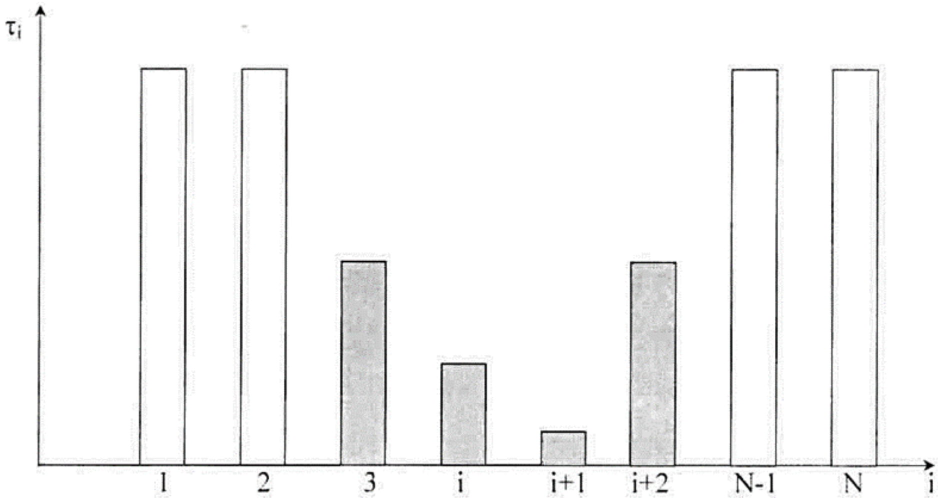

Fig. 3.8 Distribution of time intervals of the recorded reflected signal

The volume of an arbitrary body is determined if its geometric dimensions are known. Most ground-based objects of artificial origin can be approximated by simple geometric shapes, so their volume can be determined if the geometric dimensions such as length, width, diameter are known, which allow to calculate the area of the object base and height.

The calculation of the base area of an irradiated object is performed as follows: the number of MRR elements on which the base of the object is projected is multiplied by the value $S_1=[2\alpha_p D(K_p+1)]^2$, which characterises the projection area of a single element of the receiver onto the image plane, taking into account the relative distance between the matrix cells (radiation receivers).

In order to determine the number of MRR elements that record the base of an object, it is necessary to determine the serial numbers of its elements on which the boundaries of the object i_{bl}, i_{br} and the boundaries of the base of the object i_{fl}, i_{fr} are projected for each receiver line. This task is performed using an algorithm for processing three-dimensional images of ground reference points. The result of processing the three-dimensional images is a matrix, each element of which corresponds to a separate element of the MRR, and which stores the value of the time interval τ_{ij}. As input information for the algorithm, the following are given: a matrix of time intervals, angles of the object viewing in the vertical θ and horizontal φ planes, the value of S_1, M - the number of receiver rows and the number of elements in one row - N.

The algorithm for processing is based on the application of the derivative method (section 3.1) and is performed as follows: a three-dimensional image of a ground object in the form of a time interval matrix (TIM) is analysed by rows and columns. Row-by-row analysis provides information about serial numbers of the TIM elements that record the width of the boundaries of the entire object (i_{br}, i_{bl}) and the boundaries of the object's base (i_{fl}, i_{fr}). The analysis by columns, in turn, provides information on the serial numbers of the elements and MRR rows, which record the boundaries of the object in length (j_p, j_k).

Firstly, the first and second derivatives of the time intervals for each line (τ'_p and τ''_p) are calculated using the following formulas:

$$\tau'_{p_{i,j}} = \tau_{p_{i+1,j}} - \tau_{p_{i,j}} ;$$

$$\tau''_{p_{i,j}} = \tau'_{p_{i+1,j}} - \tau'_{p_{i,j}} .$$

Further, the second derivatives of the time intervals are analysed. The serial numbers of the first and last elements of the row with a second derivative greater than zero are recorded, and they are denoted as i_{bl} and i_{br}, respectively. Also, the serial numbers of the first and last elements of the row with the second derivative less than zero are recorded, they characterise the boundaries of the object's base and are denoted respectively as i_{fl} and i_{fr}. Such an analysis is performed for each row of the time intervals matrix. However, in addition to the time intervals representing the base of the object, the time intervals representing the underlying surface and front and side edges of the object are also recorded in the TIM. To avoid errors in the calculations, it is necessary to disregard the TIM elements that recorded the above surfaces, i.e. to determine the beginning and end of the object's base only. Therefore, at the second stage, the first and second derivatives of the time intervals for each column of the TIM (τ'_c and τ''_c) are calculated using the following formulas:

$$\tau'_{c_{i,j}} = \tau_{c_{i,j+1}} - \tau_{c_{i,j}} \quad ;$$
$$\tau''_{c_{i,j}} = \tau'_{c_{i,j+1}} - \tau'_{c_{i,j}} .$$

The analysis of the second derivative of the TIM column allows us to register the serial numbers of the first and last elements of the column where the second derivative is greater than zero. The sequence numbers of these elements are denoted as j_p and j_k, respectively, and characterise the beginning and end of the object base for this column. This analysis is performed for each column of the TIM.

3.4 Algorithm for feature extraction for terrestrial object recognition

The input information for the ground objects features formation algorithm includes: the object viewing angles in the vertical (θ) and horizontal (φ) planes and the matrix of time intervals (A).

The algorithm for the formation of geometric features consists of four main blocks: a block for calculating the first and second derivatives of time intervals (τ' and τ''), a block for determining the boundaries of the object's base (i_{fl}, i_{fr} and j_p, j_k) and a block for calculating the geometric features V and H (figure 3.9).

The procedure for calculating the first and second derivatives of time intervals is described in section 3.2. The boundaries of the object's base (serial numbers of the elements of the MRR i_{fl}, i_{fr} and j_p, j_k) can be determined by analysing the digital image of the object using the method of derivatives, section 3.3.

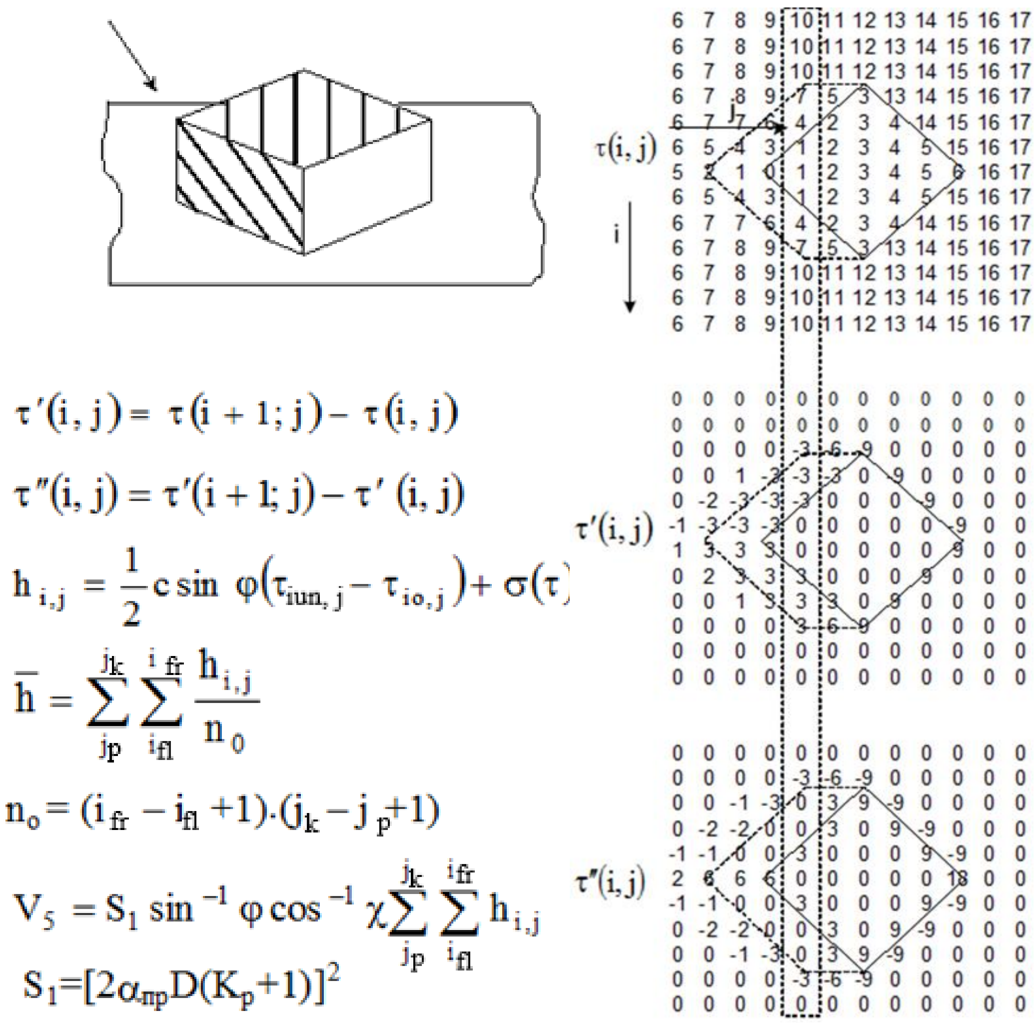

Fig. 3.9 Algorithm for forming geometric features using the method of derivatives

The calculation of the geometric features of the object: volume (V) and its average height (H) can be described in the following way. The area of the object's foundation (base) is given by the expression:

$$S_{found} = \sin^{-1}\theta S_1 \sum_{j_p}^{j_к} \left(i_{fr,j} - i_{fl,j} + 1\right)$$

where: j_p, j_k - are the numbers of the MRR rows, the elements of which record the boundaries of the object's base in the longitudinal direction.

To determine the height of a part of an object projected onto the j-th MRR row, information about the angle of view of the object in the vertical plane θ and the difference between the time intervals recorded by the elements of the j-th MRR row from the upper base of the object $\tau_{ib,j}$ and the underlying surface $\tau_{iun,j}$ is needed.

On figures 3.3 and 3.4, these elements are denoted as: i_0 and i_{un}, respectively. Then, according to the figure 3.6, the maximum height H_j of the irradiated object projected onto the j-th line of the MRR will be determined by the following expression:

$$H_j = \frac{1}{2} c \sin\theta \left[\left(\tau_{iun} - \tau_{\min,j}\right) + \sigma(\tau)\right] \qquad 3.6$$

where: c - is the propagation speed of laser radiation; σ(τ) is the standard deviation of the time interval measurement error; $\tau_{\min,j}$ - is the time interval corresponding to the highest element recorded by the j-th MRR line.

The average height $\overline{H}_j$ of the part of the irradiated object projected onto the j-th line of the receiver can be written as:

$$\overline{H}_j = \frac{1}{2} c \sin\theta \left\{\left[\sum_{i_{fl}}^{i_{fr}} \left(\tau_{iun,j} - \tau_{io,j} + \sigma(\tau)\right)\right]\left(i_{fr,j} - i_{fl,j} + 1\right)^{-1}\right\} \qquad 3.7$$

The height of the object element H_{ij} (the height above the underlying surface of the element upper base) which falls within the field of view of a separate i-th j-th MRR element, is determined by the formula:

$$\overline{H}_{ij} = \frac{1}{2} c \sin\theta \left(\tau_{iun,j} - \tau_{io,j} + \sigma(\tau)\right) \qquad 3.8$$

In this case, the average height H of the entire object is written by the expression:

$$H = \left(\sum_{j_p}^{j_k} \sum_{i_{fl}}^{i_{fr}} H_{i,j}\right)\left[\sum_{j_p}^{j_k} \left(i_{fr,j} - i_{fl,j} + 1\right)\right]^{-1} \qquad 3.9$$

Using formulas (3.6-3.9), we can write four expressions for determining the object’s volume:

$$V_1 = S_1 \sin^{-1}\theta \cos^{-1}\varphi \sum_{j_p}^{j_k} \left[\left(i_{fr,j} - i_{fl,j} + 1 \right) \cdot H_j \right] \quad 3.10$$

$$V_2 = S_1 \sin^{-1}\theta \cos^{-1}\varphi \sum_{j_p}^{j_k} \left[\left(i_{fr,j} - i_{fl,j} + 1 \right) \cdot \overline{H}_j \right] \quad 3.11$$

$$V_3 = S_1 \sin^{-1}\theta \cos^{-1}\varphi \left[\sum_{j_p}^{j_k} \left(i_{fr,j} - i_{fl,j} + 1 \right) \right] \cdot H \quad 3.12$$

$$V_4 = S_1 \sin^{-1}\theta \cos^{-1}\varphi \sum_{j_p}^{j_\kappa} \sum_{i_{fl}}^{i_{fr}} H_{i,j} \quad 3.13$$

The formulas (3.10 - 3.12) are identical in structure and differ only in the height values. The volume calculated by these formulas is the sum of elementary volumes, each of which is equal to the product of the area part of the object base, projected on the MRR row and the corresponding height value (H_j, $\overline{H}_j$, H). At the same time, formula (3.13) defines the volume as the sum of elementary volumes of the object fragments registered by the MRR elements.

Use of only one feature - volume - for object recognition may not be sufficient, since objects with the same volume may have different geometric dimensions. Therefore, in addition to the volume feature, it is advisable to use such a feature as the average height of the object when recognising ground objects. The average height of an object can be determined by three formulas:

$$H_1 = \frac{1}{\left(j_k - j_p + 1 \right)} \sum_{j_p}^{j_\kappa} \overline{H}_j \quad (3.14)$$

$$H_2 = \left(h_{o_{max}} - h_{o_{min}} \right) / 2 \quad (3.15)$$

$$H_3 = \left(\sum_{j_p}^{j_\kappa} \sum_{i_{fl}}^{i_{fr}} h_{i,j} \right) \left[\sum_{j_p}^{j_\kappa} \left(i_{fr,j} - i_{fl,j} + 1 \right) \right]^{-1} \quad (3.16)$$

Thus, there are several ways to determine objects geometric features. These geometric features depend on many components, it is most appropriate to use expressions

3.13 and 3.16 to determine these features. The algorithm for forming geometric features using formulas 3.13 and 3.16 is shown on figure 3.10:

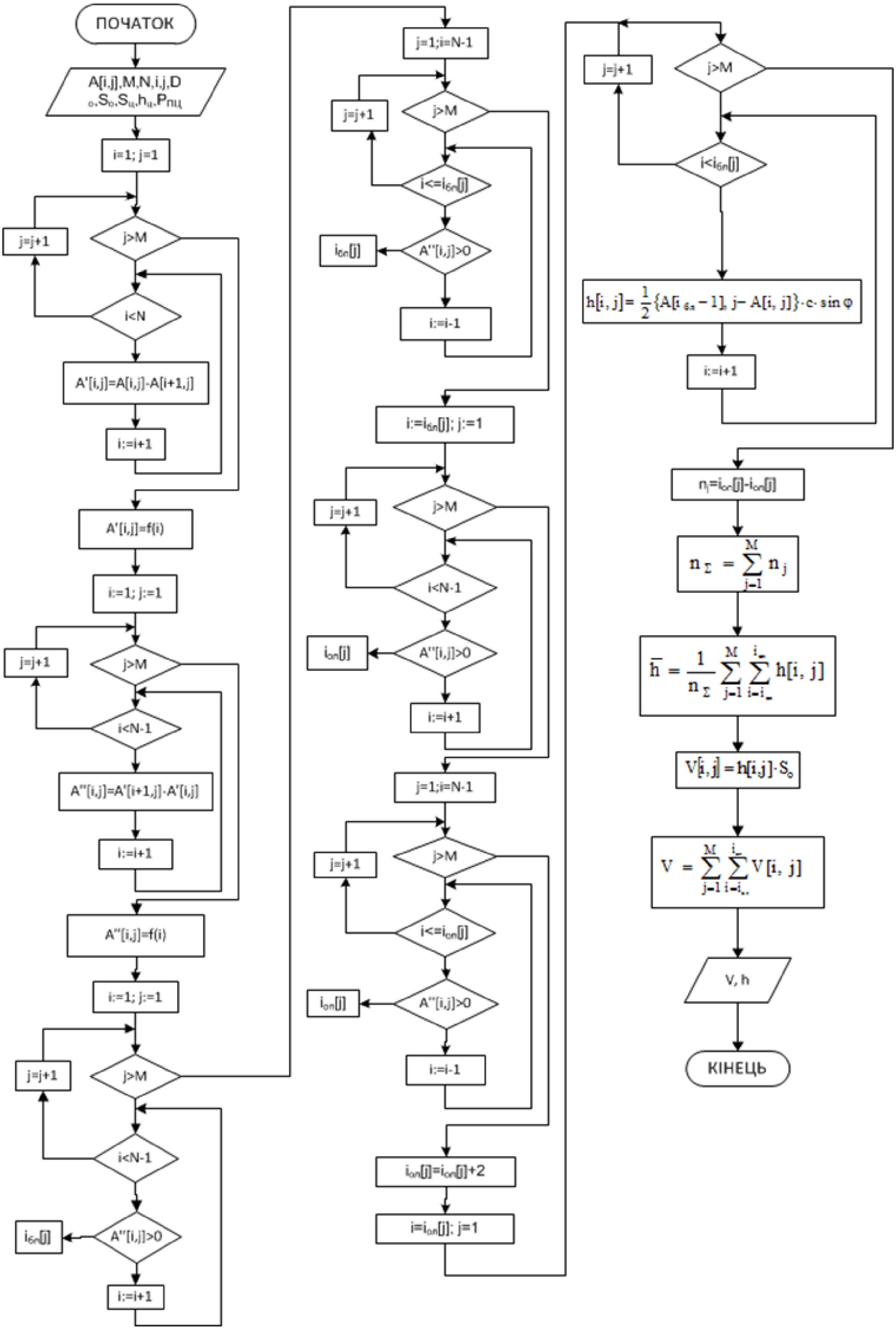

Fig. 3.10 Algorithm for forming geometric features

The calculated features of objects using the classification algorithm (figure 3.11) are compared with the features of reference points that are included to the flight plan database and have precisely defined coordinates. If the probability of matching both object features (volume and average height) and flight plan data is high (about 0.8), then we can accurately indicate the position of the aircraft or correct the position of another navigation system.

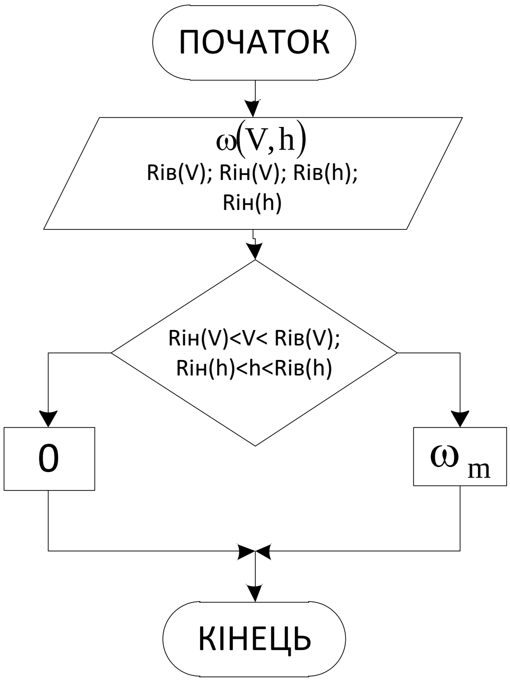

Fig. 3.11 Reference points classification algorithm

LiDAR SCNSs gives the possibility to form a 3D images of ground surface. Processing of such three-dimensional images allows to get more reference points features than from 2D systems.

To determine the geometric features of an irradiated object, it is necessary to determine the boundaries of the object and its shape. To do this, we can use the differential method, which is based on the use of the geometric content of the first and second order derivatives to functions that approximate envelope matrices of time intervals.

Volume provides a comprehensive characterization of a three-dimensional geometric figure. However, using only volume feature for object recognition might not be sufficient, as objects with identical volumes can vary in geometric dimensions. Therefore, besides volume, the average height of the object is recommended to use for objects recognising.

CONCLUSION

Improving navigation accuracy is a key objective in facilitating the expansion of air transport by meeting the necessary aviation safety standards. Due to the imperfection of other navigation systems, it is imperative to introduce an additional system to increase flight safety through the creation of redundant navigation data. The modern survey-comparative automatic navigation system can fulfill this need for essential redundancy and is based on the principle of comparing of the reference object, coordinates of which are known, with the observed one. If there is a match, determine the aircraft coordinates relative to this recognized object.

The core principle of such system involves pinpointing an aircraft's location by comparing known terrain or ground reference points, whose coordinates are either depicted on a map or stored in the memory of a navigational computing device, with the actual observed surroundings. If a match is found, the aircraft's position can be determined with probability near 90%. Moreover, they are autonomous and provide integral reproduction of the full set of navigation data, can interact with on-board digital computers.

Comparative analysis showed that use of a laser sensor, called LiDAR, in SCNS, which has the possibility to form a 3D ground surface images has the greatest potential for implementation. LiDAR provides the largest amount of information compared to other sensors and has a high resolution, which in turn increase the accuracy of object recognition.

Formation of three-dimensional images of ground reference points, required for recognition tasks is achieved by sensing them with laser pulses of nanosecond duration and analysing the spatial and temporal structure of the reflected signal. These allows to obtain a 3D image of ground objects in the form of a matrix of time intervals from an aircraft on a certain trajectory, where the elements of the matrix occupied by the object image, determine information about its geometric dimensions (length and width), and information about time intervals recorded in each element of the matrix determines its spatial characteristics.

It is proposed to apply a differential method for analysing 3D images of ground reference points, which is based on the use of the properties of first- and second-order derivatives when applied to functions that approximate envelope matrices of time intervals. This approach makes it possible to reproduce the boundaries of an object against the background of the underlying surface, to find the basic shape elements, as well as their number and size.

For the classification of ground objects, it is proposed to use two recognition features

- the volume of the object;
- and its average height.

The calculated features of objects using the classification algorithm are compared with the features of reference points that are included to the flight plan database and have precisely defined coordinates. If the probability of matching both object features (volume and average height) and flight plan data is high (about 0.8), then we can accurately indicate the position of the aircraft or correct the position of another navigation system, for example INS.

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