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DESIGN AND FUNCTIONAL FEATURES OF THE SMALL-SIZED ANTENNA ARRAY «COMETA-M»

In the article, the results of research on the design and functional characteristics of «Cometa-M» are presented. It is a compact adaptive antenna array with an integrated satellite navigation receiver, which is actively used by the enemy against Ukraine as a key component of the navigation system for unmanned aerial vehicles and other aerial attack means.

The technical specifications and operational features of «Cometa-M» have been investigated. During the research, the construction structure and the purpose of its key components were determined. Based on the research results, a structural diagram was compiled and the operating principles of «Cometa-M» were described.

Keywords: *DAA, antenna array, anti-jamming, beam pattern, navigation system, CRPA, GNSS, Cometa-M, UAV.*

INTRODUCTION

A key element of various types of UAVs, ballistic and cruise missiles, which are widely used in the armies of many countries, are satellite navigation systems (SNS). It should be noted that special systems for protecting the respective GNSS from active interference have recently been created exclusively on the basis of digital antenna arrays (DAA) with the implementation of adaptive signal reception algorithms [1]. The main feature of DAA, as is known [1−13], is that they are able to actively change the shape of their radiation pattern to reduce the impact of interference from electronic warfare (EW). Due to digital signal processing, such an antenna array can adaptively reduce the level of interfering signals, which makes it effective for operation in complex electromagnetic environments.

Given the small number of antenna elements, the interference immunity of the DAA in on-board SNS largely depends on their technical characteristics and functional capabilities to counteract interference while maintaining the required quality of reception of useful signals.

The russian federation pays great attention to the development of electronic countermeasures against interference with on-board satellite navigation systems «Cometa-M», which use small-sized DAAs. This approach has been implemented in the Orlan-10 UAV, Shahed-136 (Geran-2) strike UAVs, and the UMPK (Universal Module Planning and Correction) of guided aerial bombs.

The purpose of the article is to perform a detailed analysis of the technical design and functional features of the «Cometa-M» SNA modules for further determination of their properties and interference resistance.

ANALYSIS OF KEY RESEARCH AND PUBLICATIONS

The analysis of the main publications on the study of designs and features of the use of digital charting technology to ensure the interference immunity of satellite navigation systems, given in [1], was a pioneering work in this area in the former USSR. Over the past 10 years, there has been a widespread introduction of DAAs into satellite navigation systems, accompanied by a significant number of scientific papers and publications of foreign origin on the practical implementation of SNS signal processing in such antenna arrays. In addition to those mentioned in [1], we can mention, for example, articles [14−16]. The term CRPA (Controlled Reception Pattern Antenna) is most often used in the context of using DAA for navigation systems, which was introduced by developers solely as a marketing step to create the illusion of having something original in their developments. In fact, CRPA is a typical receiving DAA, which uses long-known methods of signal processing and formation of zeros in the directional pattern in the directions of interference. Such CRPAs have become widespread in radar, hydroacoustics, ultrasound diagnostics and communication systems [2−13]. For example, at Stanford University, a DAA with the ability to direct the beam and adaptively generate zeros was considered as a CRPA, which is presented in [14]. Studies have been conducted on the impact of GPS receiver architecture on the operation of CRPAs. The impact of different receiver architectures on signal quality and interference suppression efficiency was assessed. The influence of the sequence of operations for generating the signal pattern and correlation, the number of quantisation levels and the dynamic range of ADCs (analogue-to-digital converters) was analysed.

Taking into account the different features of carriers in onboard SNSs, both 4 and more antenna elements are used to create a CRPA. Paper [15] presents the development and testing of a 7-element controlled radiation pattern antenna (S-CRPA) with a diameter of 7 inches. An approach using special materials was applied, which allows reducing the physical dimensions of the antenna system without losing phase characteristics. The article presents test results that demonstrate the effectiveness of the corresponding CRPA in suppressing interference and ensuring reliable reception of GPS signals.

Considerable attention is also paid to the algorithms and methods used to process GPS, GLONASS, Galileo, Beidou signals in the DAA SNS. Article [16] discusses methods of forming «zeros» and «rays» of the radiation pattern of the antenna array of navigation equipment. These methods are aimed at suppressing signals from powerful point sources of interference and increasing the sensitivity of receiving equipment. Additional methods of filtering and suppression of in-band narrowband interference are also considered [17].

According to the results of the analysis of publications, it should be noted that they consider new methods and approaches to the creation of various types of DAA/CRPA, improvement of GNSS receivers' performance characteristics aimed at ensuring the SNS interference protection.

RESEARCH RESULTS

The analysis of the structure and design features of the «Cometa-M» product indicates its high constructive manufacturability. It should be noted that with rather small dimensions of 100 mm x 100 mm x 30 mm (LxWxH), the product managed to implement a 4-channel DAA, which is capable of adaptively changing the antenna pattern depending on the existing interference. At the same time, the «Cometa-M» module contains a GNSS receiver integrated into its design. That is, this product provides a solution to the navigation task of determining the location with an accuracy that depends on the GNSS receiver used and spatial-frequency filtering of interference signals.

Let's consider the design and main elements that make up a typical version of the «Cometa-M» device used in 2022 as part of the Orlan-10 UAV. The appearance of the main signal processing board with the designation of the main elements is shown in Figs. 1, 2.

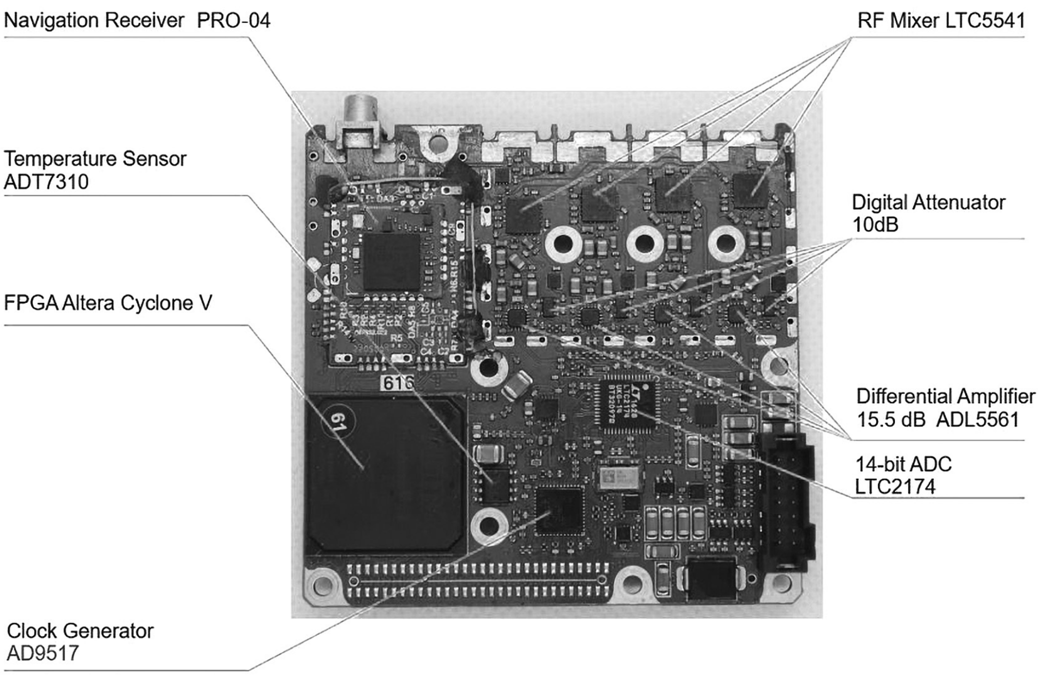
Structurally, all elements of the «Cometa-M», except for the patch antennas, are placed on a single board with a high density of filling on both sides. On one side, there are Altera Cyclone V FPGAs [18], a PRO-04 navigation receiver [19], LTC5541 RF mixers [20] and ADL5561 differential amplifiers [21], LTC2174 UKG-14 14-bit 4-channel analogue-to-digital converter (ADC) [22], AD9517-4ABCPZ clock generator with 12 outputs [23], MAATSS0018 10dB digital attenuators [24], and ADT7310 16-bit precision temperature sensor.

The backside of the board contains an 8 Mbyte EPCQ64A flash memory [25], an integrated frequency synthesiser and an ADF4360-4 oscillator [26], a high-speed single-channel TxDAC AD9755 [27] with two multiplexed 14-bit ports, an active LT5560 mixer [28], bandpass filters P4 and P14, a low-noise DC/DC converter LTM4613V [29] with an input voltage of 5V – 36V and current up to 8A, 3-output low-voltage DC/DC voltage regulator LTM4615V [30].

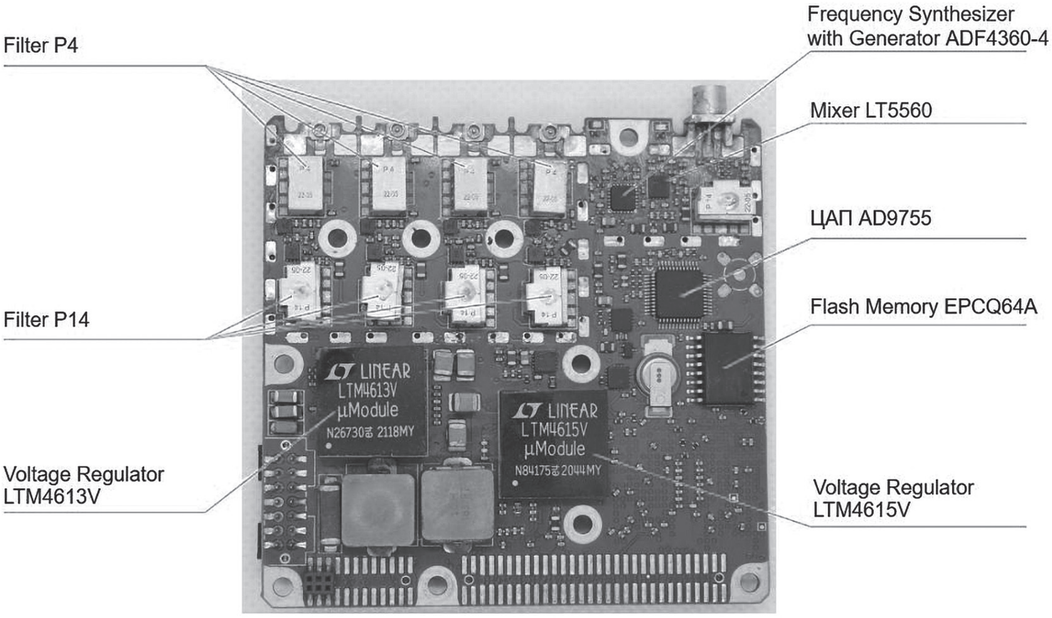
Taking into account the complexity of the device and the multilayer topology of the board, to determine the capabilities and principles of functioning of this module, an important part of the research is to determine the characteristics of the main elements and study their interaction. The defined technical characteristics of the main components are shown in Table 1.

The research was hampered by a lack of information about the characteristics of specific components that are extremely difficult to identify, but nevertheless affect signal processing. For example, after the signal is received from the antenna elements, each receiving channel is frequency selected using a bandpass filter. Since the characteristics of the P4 and P14 filters are unknown, they were determined by measurements using the NanoVNA portable vector network analyser and NanoVNA Server 0.6.2 software. The results of the measurements, namely the scattering parameters (S-parameters S11 (reflection coefficient) and S21 (transmission coefficient)), as well as the SWR of the filters are shown in Figs. 3 – 6.

According to the results of the measurements, the central frequency of the filter marked «P 4» is 1608 MHz, the bandwidth is 74.9 MHz (-3 dB level), and the maximum transmission coefficient is - 3.25 dB at a frequency 1609.4 MHz. For the filter marked «P 14», respectively,



F i g . 1. View of the signal processing board with the main elements



F i g . 2. View of the signal processing board (back side) with the main elements marked

T a b l e 1 . Technical characteristics of the main components of the «Cometa-M»

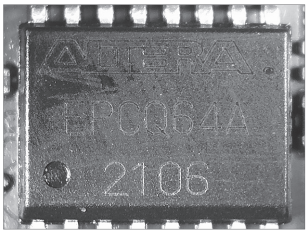
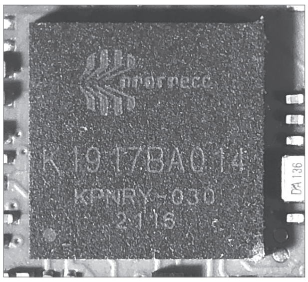
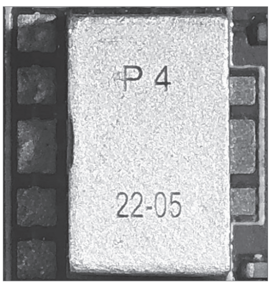
No.	Image	Description
1		**ALTERA Cyclone V 5CEFA7F23I7N F BBCAU2031A TAIWAN S028MK39 314FA0N0A** Programmable logic integrated circuit (PLIC) Number of logical elements: 149,500; number of adaptive logic modules (ALMs): 56,480; built-in memory: 7.696 Mbit I/O ports: 240. maximum operating frequency: 925 MHz supply voltage: 1.1B Operating temperature: -40°C to +100°C housing: 484-ball Fine-Pitch Ball Grid Array (FBGA)
2		**ALTERA EPCQ64A 2106** The EPCQ64A flash memory is used to store configuration data for the FPGA Capacity: 64 Mbit (8 Mbyte) Interface: SPI, Dual SPI and Quad SPI Supply voltage: 2.7 V to 3.6 V
3		**K1917BA014 KPNRY-030 2116** The PRO-04 GNSS receiver is a navigation device developed in russia by «NIIMA Progress» System support: GLONASS, GPS and Galileo Coordinate determination time: 27 s for cold start, 25 s for warm start, 2 s for hot start and 1 s for recapture, Sensitivity: -145 dBmW in search mode and -161 dBmW in tracking mode. Operating temperature: -40 °C to 85 °C
4		**Bandpass filter P4** central frequency 1608 MHz 75 MHz bandwidth (at -3 dB level)

Table 1. (continued)

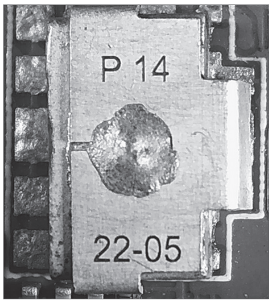
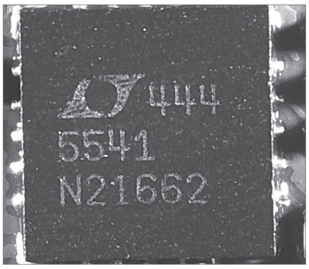
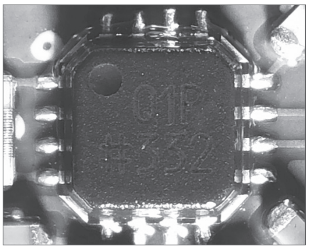
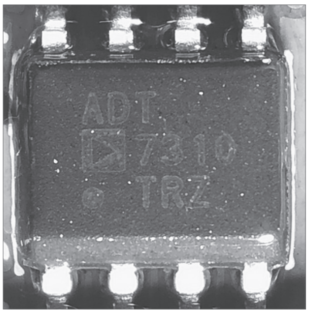
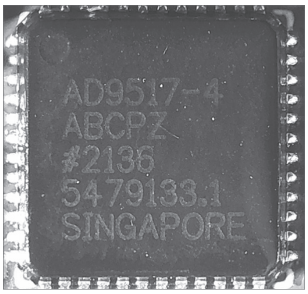
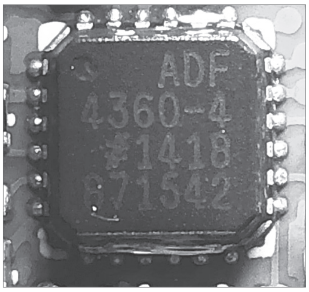
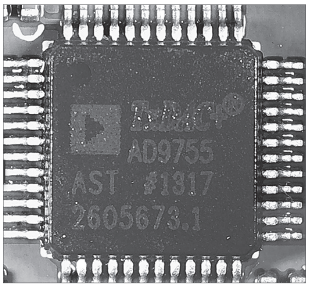
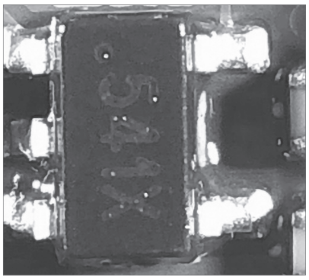
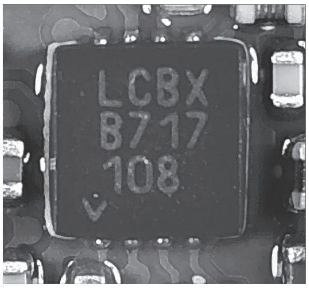
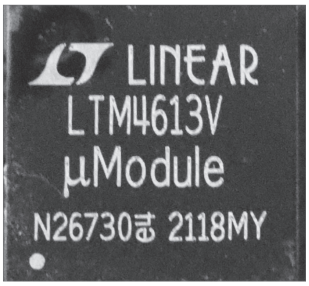
No.	Image	Description
5		**Bandpass filter P14** central frequency 1590 MHz 53 MHz bandwidth (at -3 dB level)
6		**444 5541 N21662** LTC5541 radio frequency mixer with frequency reduction for the range from 1.3 GHz to 2.3 GHz Gain: 7.8 dB Noise figure (NF) 16 dB for blocking signal up to +5 dB. Case type: 20pin QFN. Operating temperature: -40 °C to 85 °C
7		**Q1P #332** Differential amplifier ADL5561 Fixed gain: 6 dB, 12 dB or 15.5 dB Low noise and distortion levels Used as a driver for high-speed ADCs from 8 to 16 bits Case type: LFCSP-16 Operating temperature: -40 °C to 85 °C
8		**1628 LTC2174 UKG-14 BT32097 e3** 14-bit analogue-to-digital converter (ADC) number of inputs for simultaneous digitisation - 4; sample rate - up to 105 MSPS; data interface - LVDS serial; supply voltage 1.7V-1.9V; operating temperature from -40 °C to +85 °C
9		**ADT 7310 TRZ** ADT7310 precision 16-bit digital temperature sensor with SPI interface, accuracy ±0.5 °C operating temperature: from -55 °C to +150 °C
10		**AD9517-4 ABCPZ #2136 5479133.1 SINGAPORE** AD9517-4ABCPZ clock generator with 12 outputs and built-in voltage controlled oscillator (VCO), with a frequency range from 1.45 GHz to 1.80 GHz. One differential or two single-pole input signals. Input: LVPECL, LVDS or CMOS signals, Output: LVPECL with a frequency of 1.6 GHz, two pairs of 800 MHz LVDS outputs. Operating temperature: -40 °C to +85 °C Case type: 48 pin LFCSP

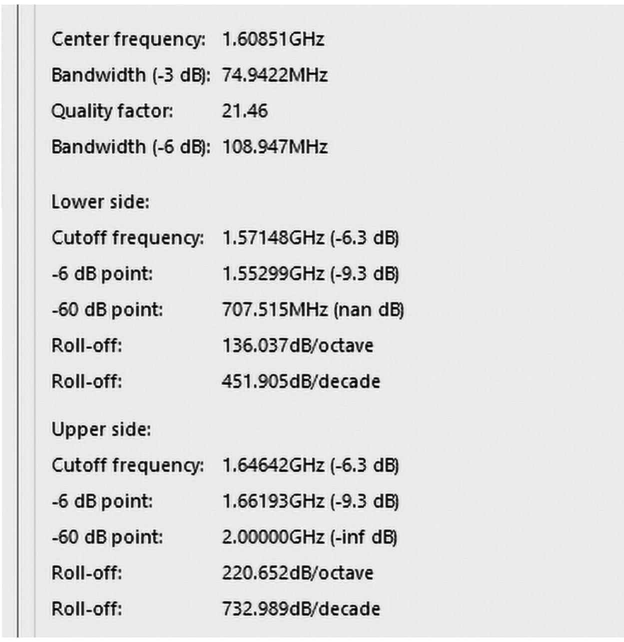
Table 1. (continued)

No.	Image	Description
11		**ADF4360-4 #1418 871542** Integrated frequency synthesiser and oscillator ADF4360-4 Provides a high level of stability and accuracy of generated signals Output frequency range: 1450 MHz to 1750 MHz. It has the ability to divide the output frequency by 2, which allows you to get frequencies in the range from 725 MHz to 875 MHz. Power supply from 3.0 V to 3.6 V. Programmable output power level and dual-module 8/9, 16/17, 32/33 pre-divider for precise frequency selection. Three-wire serial interface. Operating temperature from -40 °C to +85 °C
12		**TxDAC AD9755 AST #1317 2605673.1** High-speed single-channel DAC with two multiplexed ports; Bit depth −14 bits. Up to 300 MSPS update speed; high level of signal purity; built-in PLL to double the clock frequency; 3.0 V to 3.6 V power supply; Case type: 48-pin LQFP
13		**541X** MAATSS0018 10dB digital attenuator for frequencies up to 2GHz Maximum power for 500 – 2000 MHz: +34 dBm Operating temperature: from -40 C° to +85 C°
14		**LCBX B717 108** LT5560 high performance broadband (0.01MHz to 4GHz) active mixer Gain of 2.4 dB Power supply: 2.7 V to 5 V Case type: 3×3mm DFN
15		**LTM4613V** Ultra low noise DC/DC converter Input voltage: 5V − 36V; Output voltage: 3.3V − 15V (adjustable with an external resistor); Output current: up to 8A Case type: LGA-133 (15mm × 15mm × 4.32mm) Operating temperature: -40 °C to +125 °C
16		**LTM4615V** three-output low-voltage DC/DC voltage regulator, includes overvoltage protection, overcurrent protection, thermal shutdown, programmable soft start function Input voltage: 2.375 V − 5.5 V for DC/DC converters and 1.14 V − 3.5 V for VLDOs (very low voltage drop). Output voltage: 0.8 V – 5 V for two DC/DC converters, each with an output current of up to 4A, and 0.4 V − 2.6 V for VLDO with an output current of up to 1.5 A. Case type: LGA-133 (15mm × 15mm × 4.32mm) Operating temperature: -40 °C to +125 °C

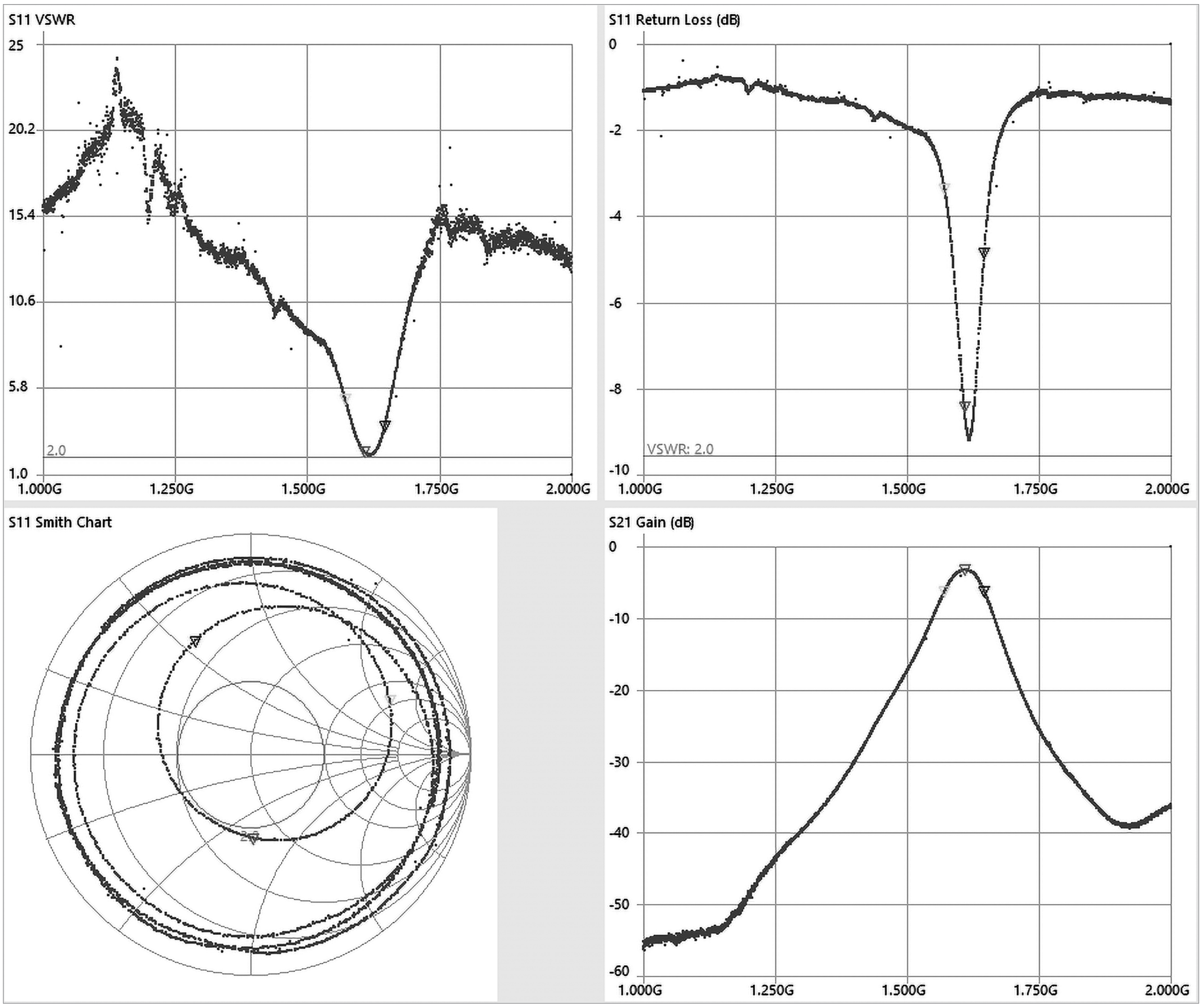
the central frequency of 1590 MHz, the passband 53 MHz (-3 dB level), and the maximum transmission coefficient level - 4.9 dB at a frequency 1580 MHz were obtained.

It should be noted that according to the bandwidth measurements, the «P4» and «P14» filters are highly specialised and designed to filter signals from global navigation systems in the L1 range of GPS, GLONASS, and Galileo.

At the same time, it is worth noting that these filters are much less suitable for use with the Beidou navigation system, which has a centre frequency 1561 MHz. According to the defined frequency characteristics, the filters will introduce additional attenuation for a signal of more than 3 dB, since the Beidou operating band is outside the filter's passband at -3 dB. This device has a built-in PRO-04 GNSS receiver that does not support data acquisition from the Beidou system, so the use of filters with these characteristics is quite natural, but the «Cometa-M» design is designed to be used with different GNSS receivers, given the prepared space for mounting the receiver board on the «Cometa-M» main board. This fact is confirmed by studies of other «Cometa-M» samples produced later, as subsequent versions use a wider operating range and other Beidou-enabled receivers.



F i g . 4. The results of the analysis of the filter parameters marked «P 4», obtained using NanoVNA Server 0.6.2 software



F i g . 3. Measurement results of the frequency characteristics of the filter marked «P 4»

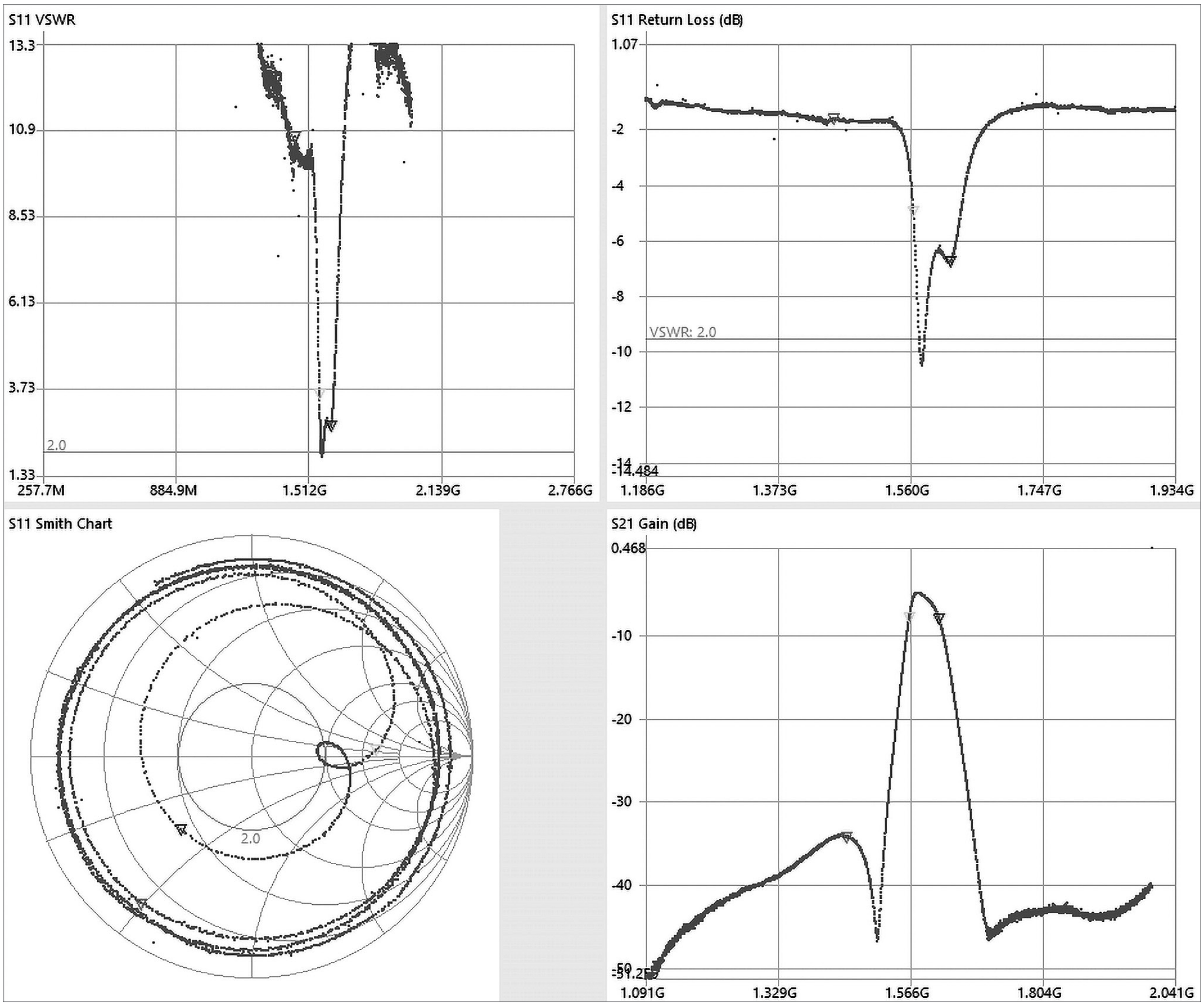


Fig. 5. Measurement results of the filter parameters marked «P 14»

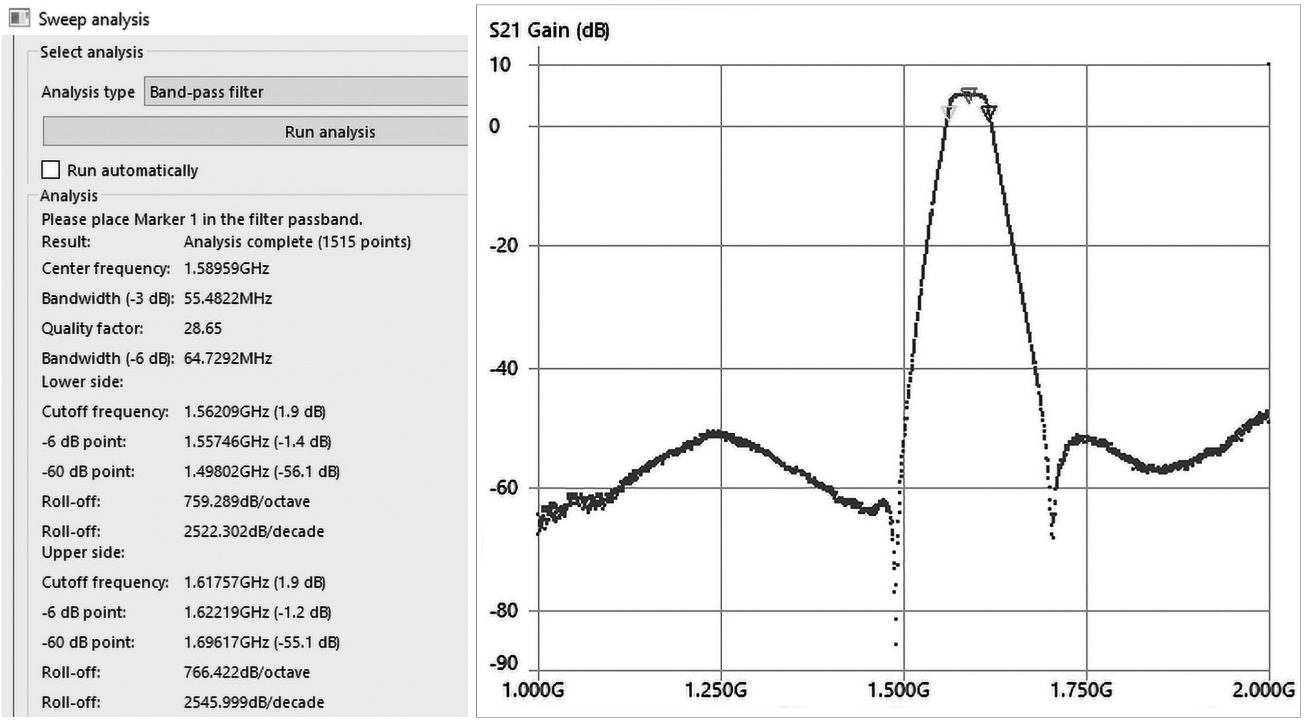
Center frequency:	1.59024GHz
Bandwidth (-3 dB):	53.1529MHz
Quality factor:	29.92
Bandwidth (-6 dB):	70.6504MHz
Lower side:	
Cutoff frequency:	1.56388GHz (-8.0 dB)
-6 dB point:	1.55761GHz (-11.1 dB)
-60 dB point:	1.33138GHz (nan dB)
Roll-off:	646.080dB/octave
Roll-off:	2146.233dB/decade
Upper side:	
Cutoff frequency:	1.61704GHz (-8.0 dB)
-6 dB point:	1.62826GHz (-11.0 dB)
-60 dB point:	2.00000GHz (-inf dB)
Roll-off:	515.895dB/octave
Roll-off:	1713.767dB/decade

Fig. 6. The results of the analysis of the filter parameters marked «P 14», obtained using NanoVNA Server 0.6.2 software

For a more detailed assessment of the frequency characteristics of the SNS device, the bandwidth of the input circuit «antenna − bandpass filter − amplifier − bandpass filter» was measured, which directly sets the limits of the operating range of the «Cometa-M». Fig. 7 shows the results of the bandwidth measurements, according to which the resulting centre frequency for the specified circuit was 1589.59 MHz with a bandwidth 55.48 MHz at the -3 dB level. At the centre frequency, the maximum level of the transmission coefficient was 4.9 dB, which indicates that the signal is amplified by the LNA (Low Noise Amplifier).

Taking into account the topology of the signal processing board of the «Cometa-M» device, the characteristics of these components, their interconnections, the manufacturer's recommendations for the use of components and the analysis of typical approaches to building the architecture of the DAC [1−13], a simplified block diagram of the device is shown in Fig. 8.

According to the scheme shown in Fig. 8, the high-frequency payload satellite signal, along with possible interference, is received by 4 patch antennas combined into an antenna unit on a single board. Each of the antenna

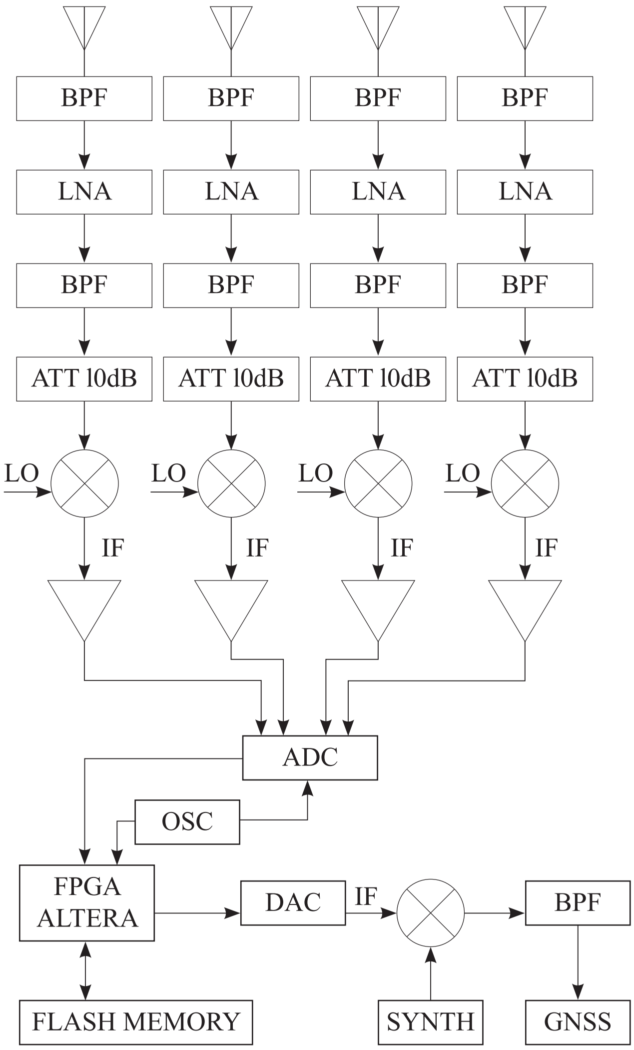


F i g . 7. The results of the analysis of the frequency response of the receiving channel segment consisting of an antenna element, a bandpass filter, and a frequency-selective amplifier

elements has a separate output, which is connected to a bandpass filter via a high-frequency cable. The received signal is then amplified using a low-noise amplifier (LNA) and passed through a bandpass filter again. The filters cut out unwanted frequencies and select only the desired frequency range where the useful signal is to be found. This eliminates noise and interference from other signals. The ATT digital attenuators in each of the 4 receiving channels adjust the signal level to reduce its power by 10 dB to prevent mixer overload, but the attenuator control mode is single-bit, i.e. the specified 10 dB attenuation can be enabled or disabled.

The mixer converts the frequency to a much lower frequency – the intermediate frequency (IF). The intermediate frequency signal is amplified using an ADL5561 differential amplifier with a controlled gain (VGA), which amplifies the IF signal to the required level. The signal is then digitised using a 14-bit LTC2174 analogue-to-digital converter and sent via a high-speed LVDS interface to an ALTERA FPGA, which processes the digital data, performs digital signal processing (DSP) algorithms and zeroing when interference is detected. The processed digital signal is fed to the AD9755 high-speed 14-bit digital-to-analog converter, which converts the digital signal to analogue. This component is used to generate a high-quality analogue signal with high accuracy and linearity from the digital data stream. The LT5560 high-frequency active mixer is used to convert the frequency of the signal. It mixes the analogue signal with a local oscillator (LO) signal to produce a new, significantly higher frequency.

The ADF4360-4 integrated voltage-controlled oscillator (VCO) frequency synthesiser is used to generate a stable local oscillator (LO) signal. The frequency of the LO signal can be precisely tuned using a phase locked loop (PLL),



F i g . 8. Block diagram of the «Cometa-M» device providing high stability and accuracy. The received high-frequency signal from the mixer is fed through a band-pass filter (BPF) to the PRO-04 GNSS receiver, where the satellite signal is processed and navigation messages are demodulated. The resulting navigation solution with defined coordinates, altitude, etc. is transferred in the form of digital data to the FPGA (PLIC), where it can be further processed and sent to the output connector of the device as the resultant data.

Taking into account the components used in the implementation of this device, their characteristics, structural scheme, as well as the approaches used in the formation of the adaptive radiation pattern, it can be argued that the following algorithm is implemented in the «Cometa-M» device.

1. The signal is received independently by each of the patch antennas, followed by filtering and amplification of signals in a certain frequency range.
2. The signals are digitised by a 4-channel ADC (LTC2174).
3. The ALTERA FPGA generates a correlation matrix of signal powers.
4. To calculate the weighting coefficients, the FPGA can use one of the adaptive algorithms for digital beamforming with maximising the signal-to-(interference-plus-noise) ratio − SINR (Signal-to-Interference-plus-Noise Ratio). This version of the algorithm is suitable for navigation systems, as it takes into account both noise and interference, which ensures reliable signal reception in conditions of intense interference.
5. Application of calculated weighting coefficients in FPGA to process an array of signals from the antenna array outputs to generate an output signal with an improved signal-to-noise ratio.
6. Continuous interference suppression is achieved by spatial filtering in the FPGA to create «zeros» in the directions of the interferers with dynamic adjustment of the weighting coefficients.

CONCLUSIONS

In the course of the study of the «Cometa-M» device, the components of which it consists were identified, their characteristics and interrelationships were investigated, a structural diagram and a simplified description of the algorithms that are most likely to be used in the operation of this device were created. The frequency characteristics of the input stages of this device, which directly form the operating frequency range for further signal processing, were measured.

According to the results of the conducted research, it should be noted the constructive manufacturability of the «Cometa-M» device, namely, with compact dimensions, a rather complex functionality based on the use of DSP is implemented to minimise the impact of interference. The wide capabilities of the ALTERA FPGA used in this device allow implementing signal processing algorithms based on the calculation of the correlation matrix of signal powers from each receiving channel, the calculation of weighting coefficients and their consideration in the formation of «zeros» in the directions of interference signals.

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КОНСТРУКТИВНІ ТА ФУНКЦІОНАЛЬНІ ОСОБЛИВОСТІ МАЛОГАБАРИТНОЇ АНТЕННОЇ РЕШІТКИ «КОМЕТА-М»

У статті представлені результати проведених досліджень конструктивних та функціональних особливостей антенної решітки «Комета-М». Об'єктом досліджень є малогабаритна адаптивна антенна решітка із вбудованим супутниковим навігаційним приймачем, яка активно застосовується ворогом проти України, як основна складова навігаційної системи безпілотних літальних апаратів та інших засобів повітряного нападу. Подібні системи побудовані на базі цифрових антенних решіток та використовуються для підвищення стійкості роботи супутникових навігаційних приймачів в умовах завад, адже призначені для забезпечення просторової фільтрації сигналів від завад.

Досліджено технічні характеристики та особливості функціонування антенної решітки «Комета-М». У ході проведених досліджень визначено структуру побудови, призначення ключових компонентів. Наведено зовнішній вигляд, короткий опис та технічні характеристики основних компонентів. За відсутності можливості однозначної ідентифікації компонентів, виміряні їх технічні характеристики. Це особливо актуально для високочастотних фільтрів, які задають робочий діапазон частот, оскільки діапазон частот, який обробляє антенна решітка, визначає навігаційні системи, сигнали з яких вона може обробити.

За результатами проведених досліджень складена структурна схема та описано принципи роботи «Комета-М», наведено послідовність обробки радіосигналу. Характеристики ключових компонентів, таких як АЦП, ПЛІС та ЦАП, визначають спроможності цієї антенної решітки щодо обробки сигналу, оскільки у даних системах важлива величина розрядності оцифрування сигналів.

Ключові слова: *ЦАР, антенна решітка, протидія завадам, діаграма спрямованості, навігаційна система, CRPA, GNSS, «Комета-М», БпЛА.*

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