Design of a push-broom multi-beam radiometer mapping system based on toroidal SAT TV antenna

O A Gerasimov, D V Drozdov and Yu V Rybakov

Department of Geophysical Monitoring and Research, Voeikov Main Geophysical Observatory, ul. Karbysheva, 7, 194021, St. Petersburg, Russian Federation
E-mail: olgrs@mail.ru

Abstract. A functional diagram of a surface radiation mapping microwave radiometer system is presented. The system is proposed for use in agriculture, to map fields soil moisture, effectiveness of draining systems, etc. It has also many other useful applications, such as early detection of subsurface fires in peats and many more. Previous single-beam systems used a number of passes and long lasting flight times to obtain a map of the underlying surface. Some multi-beam systems used bulky electromechanical scanning antennae unsuitable for light aerial vehicles. Thus those systems were unaffordable to use for small agricultural businesses due to high production and operational costs. Authors propose low-cost microwave push-broom system that is based on a toroidal antenna and other budget components mass-produced for satellite television. Due to its low weight the complex can be mounted on an unmanned aerial vehicle. The microwave complex is designed to use six to fourteen radiometer channels of different bands on a single toroidal antenna. This allows to form the underlying surface map containing radiation data with limited number of aircraft passes significantly reducing survey time. The possibility of simultaneous operation in the Ku and C bands has been successfully investigated.

1. Introduction
Remote sensing is currently a powerful tool for investigating and monitoring the characteristics of the underlying surface. A huge amount of experimental work [1-2] was carried out, which confirmed the effectiveness of this direction for solving urgent problems in agriculture and land reclamation, for protecting forests and peat bogs from fires. To solve these problems, microwave radiometers of cm and dm bands are required, which have sufficient penetrating power, high resolution on the surface, and good instrument sensitivity, i.e. it is necessary to place microwave systems on low-flying light aircraft, and even better on unmanned aerial vehicles (UAVs), which are much cheaper to operate.

Such projects, for example, were considered in [3-4], but they used single-beam (single-pixel) devices, which required a lot of time to compile brightness temperature surface maps. In [5], examples of such maps are presented, obtained using the Radius-M complex, operating on the principle of electro-mechanical sequential scanning by the radiation pattern, however, such systems are cumbersome to place on UAVs and they have limitations on obtaining high sensitivity.

More effective for these purposes are multi-beam radiometers of parallel action, in which a line of beams (pixels) is formed along a line perpendicular to the direction of flight (push-broom system), with each pixel representing a separate radiometric channel. The first samples of L band push-broom radiometers for obtaining soil moisture maps were described in [6-8] and were used on a light aircraft. In [9], a long-term monitoring of changes in the moisture and vegetation of the reference fields was
carried out, which confirmed that while the measurements in the L band are the most informative, information obtained in the C and Ku bands can be used, too.

This conclusion is very important, since in the L band it is impossible to get a noticeable number of beams at a small aperture (in the Radius-M system, for example, only 2 beams are formed). This work aims to explore the possibility of creating a push-broom radiometer based on mass-produced satellite television toroidal antennae for the operation of such systems in several bands.

2. Push-broom microwave systems basics
The creation of mapping microwave complexes for monitoring the parameters of the underlying surface is an important task, since only a brightness map allows one to obtain clear and effective information about the state of the studied parameters. Examples of microwave radiometric maps compiled in order to identify wetlands and analyze the state of dikes, showing the distribution of radiation from the underlying surface in the L, C and X bands, were obtained using the Radius microwave complex developed by Vega.

However, the principle of electro-mechanical scanning has on the flip side an increase in weight and size characteristics. Modern advance in the development and production of unmanned aerial vehicles has opened up new wide opportunities for solving the problems of operational monitoring of the underlying surface parameters. A microwave complex with its relatively large antenna, receivers and power sources cannot be as light as, for example, a video camera, and for to carry it, a medium UAV with a 10–25 kg payload can be procured.

Microwave mapping can be done either through electronic deflection of the beam of a phased array, or through using a multi-beam antenna. It is proposed to use mass-produced satellite television toroidal T-90 and T-55 antennae (patent RU2000117951) as the basis of the mapping complex. A push-broom array of beams forms the underlying surface map containing radiation data. Since each beam must have its own receiving channel, the receivers should be as cheap and affordable as possible. To implement the receiving circuit, it is advisable to use ready-made television converters Ku, C and S bands. As they are produced in huge quantities, their cost is small while the quality is high. The key characteristic of the receivers - the noise temperature - now achieves 15-20 K (almost the limit achievable values in devices without forced cooling).

3. Mapping microwave radiometer complex UAV installation
Figure 1 shows some medium UAVs manufactured in Russia and Belarus, suitable for carrying microwave systems.

![UAVs](Figure 1. Modern medium class UAVs: Indela-Country (a), ZALA 421-02X (b), MBPV-37 (c).)

Figure 2a illustrates an idea of a dual-mirror toroidal antenna, and the following notation is introduced: 1 - reflector (main mirror), 2 - subreflector (auxiliary, small mirror), 3 - phase centers of feeds. In vertical section, the antenna is a dual-mirror Gregory antenna. To work in the mode of monitoring of the underlying surface, the antenna is oriented to nadir.

On figure 2 (b, c) there are vertical profiles of T-90 and T-55. The measurements of the profiles are given compared with the calculated ones (in this example, they practically coincided). Focal points are indicated.
Finding focal lines was a separate task, since this information was not disclosed by the antenna manufacturer. The measured profiles of parabolic and toroidal mirrors were plotted on a grid, where they were combined with calculated parabolas and ellipses, the focal points of which were calculated using classical formulas and plotted on the same graph. Geometric constructions were performed using a free image editor with a Python console. Automation of calculations and instant presentation of their results in a graphical form convenient for analysis was provided by a special designed software module.

The feed located on the focal line of the antenna should provide irradiation of elliptical mirror edges at a level of \(-9 \ldots -12\) dB using standard Ku and C band irradiators. When Ku feeds are mounted in standard holders side by side along the focal line, it is possible to place up to 10 receivers on the T-55 and up to 14 on the T-90.

The number of resolution elements in the line - pixels - is determined by the number of beams, and the vertical sweep is formed via carrier’s own movement. When installing a toroidal antenna in a rectangular box-shaped case, there will inevitably be hollow spaces. However, these spaces - in particular, the excess volume under the auxiliary mirror, - can be used to place the receivers of the S and L bands as a useful addition (not related to the toroidal antenna). These devices are supposed to be equipped with their own printed antennas (arrays or wave channels). Thus, a convenient basis for the implementation of a multi-beam radiometric complex for monitoring the underlying surface can be obtained.

4. Block diagram of a single band mapping microwave radiometer

Figure 3 shows a block diagram of a mapping microwave Ku band radiometer based on a toroidal antenna. There are 10 beams (if T-55 is used) for Ku band. Each channel (beam) corresponds to its feed, its low-noise receiving block (LNB) and its low-frequency unit, which includes a power injector, a square-law detector and an amplifying circuit. This output is connected to an analog-to-digital converter (ADC) followed by recording and processing devices.

The block diagram for the C band, as well as for the Ku+C+S combined, will be similar but with a different number of receiver channels. Using different combination of LNBs and/or irradiators the number of channels (beams) varies from 6 to 14.

The LNB power is supplied through injectors either from the UAV power supply, or from an additional power supply. Individual pixels form a horizontal sweep through the ADC. The frame sweep is formed using carrier's positional information through the on-board information-control system (ICS). The computer processes the signals and generates a proper radiation map of the underlying surface.
Figure 3. The functional block diagram of the multi-beam push-broom radiometer.

In a standard Ku band feeds (10.7–12.75 GHz) an antenna and a receiver are combined in one unit (LNB). On figure 4 (a) LNB Sharp BS1R8EL100A is shown with a corrugated horn antenna. On figure 4 (b) there is a group of Eurosky LNBs with conical dielectric resonator antennas in comparison with corrugated horn one. Both units provide irradiation of the edges of the auxiliary mirror in the Ku band at a typical -10 dB level or lower.

Figure 4. LNB Sharp BS1 R8 EL 100A (a), LNBs EuroSky pro EHKF-7107a (b).

Obviously, LNB blocks with a dielectric feed, having a smaller width, can be mounted closer to one another than the horn-corrugated ones, which opens up the possibility of increasing the number of receiving Ku channels in a single-band version.

The antenna part of the standard C band feed, as a rule, is also made in the form of a corrugated horn, but separately from the receiving device, which is interfaced through waveguide to coaxial
transitions (that negatively affects the dimensions and weight). The C band feed horn has an aperture of 160 mm and is designed to operate in the band 3.4–4.2 GHz. Beamwidths at −3, −5, −10, −15 dB levels in the E and H planes are very close to each other and very well coincide with theoretical values. The exposure level for the angle $\phi/2 = 32^\circ$ ($\Delta = 64^\circ$) corresponding to the edge of the auxiliary mirror is approximately −9 dB (theoretical value −9.3 dB) and coincides with the −9 dB level at $f = 10.7$ GHz for a standard Ku band feed.

5. Laboratory tests of radiometer prototype parts

Initially, the T-90 and T-55 antennas were designed only for operation in the Ku band. The C-channel feed was intended to work with other offset antennas. Some laboratory test were made to determine the possibility to use C band with T-55 antenna. The typical C horn was set to a position close to the center of the antenna. The theoretical value of the exposure level for an angle of 75° is 11.7 dB. The practical result for the C horn at $f = 3.93$ GHz in the 75° sector is an irradiation level of about −10 dB, and thus this horn can be used as a T-55 feed, especially since there are modifications for simultaneous reception at two polarizations, and dual C and Ku bands LNB.

Since such a feed has a weight of about 0.5 kg, and it is difficult to fix it in a standard toroidal antenna, the implementation of a lightweight C feed in the form of a printed patch antenna was considered. On figure 5 is the T-55 with four printed feeds placed on the focal line.

![Figure 5. T-55 with four printed feeds.](image)

The printed feed has an aperture of 130 by 130 mm, a thickness of 5 mm and a weight of 125 g. The antenna part of each feed is an array of five identical square patches. The reverse side contains a power divider for the feed elements.

A combined feed for the C and Ku bands is now being developed. It is formed from the above 5-element structure through removal of the central element. Such a transformation slightly negatively affects the radiation pattern, but provides a number of advantages. The power dividing scheme becomes symmetrical and uniformly excited, and the calculation of the characteristics of the array becomes a simpler task [1]. The freed up central area of the circuit board allows to integrate the Ku band horn feed (figure 6).

The installation of a combined feed of C / Ku bands on the T-90 will allow, in addition to the simultaneous use of two bands, to increase the number of generated beams. The radiation patterns of the antenna with the combined feeds are currently being investigated.
Figure 6. C band printed feed with four patch elements. There is a Ku band horn in the centre of the board.

The laboratory tests included measurements of the radiation patterns of the prototype based on a toroidal antenna and standard feeds. The feeds were moved along the focal line. In the single-band version both in the Ku and C band, the patterns have a clearly formed main lobe and intersect at a level of about minus 3 dB.

Figure 7 shows the 12.075 GHz radiation patterns of Ku feeds installed on the T-55 antenna, measured when the LNB blocks were mounted in standard holders along the focal line close to each other in a manner that allows to form twelve beams.

Duly-formed antenna patterns of a corrugated horn are a guideline for estimation of the quality of feeds of other types, which have an advantage in weight and ease of installation.

The test program for the printed feed included measurements of radiation patterns in two polarization planes for various configurations and frequencies. As an example, the figures show the patterns in E and H planes at f = 4.0 GHz for a 5-element feed (figure 8, a), for a 4-element feed
before mounting the horn (figure 8, b), and finally, for a 4-cell feed with a horn in the center of the board figure 8, c).

![Graphs a), b), and c) showing radiation patterns of different feeds.](image)

**Figure 8.** Radiation patterns of different feeds: the 5-patch feed (a), the 4-patch feed (b), and the 4-patch feed with a horn in the center (c).

A noticeable feature of the obtained patterns is the high level of side lobes (-7 dB ... -8 dB), due to the choice of the distance between the elements of this printed part. When the Ku band metal horn is placed in the center of the printed feed, the width of the main lobe of the pattern changes insignificantly, but the side level increases as it did in a previous case. Same results were observed earlier in [10], which may suppose it's an inevitable effect.

There are several ways to make the diagram better by, for example, moving Ku horn inwards and outwards the C feed board. But the general result of those test is that combined C/Ku feed is quite suitable to use with toroidal T-55 antenna.

**Conclusion**

The conducted studies show the possibility of installing microwave radiometric system on a modern medium class UAV. The goal is to use lightweight multibeam scanning system with single antenna in opposite to bulky previous systems. The achieved results indicate the practical ability to map the underlying surface in at least two bands simultaneously, which strengthens confidence in the prospect of using the antennae proposed as the basis of the radiometric complex.

The use of mass-produced satellite television components allow to form the underlying surface map by several microwave radiometers of different bands on a single antenna to form a line and the aerial vehicle movement as vertical sweep to form the frame. The functional diagram displays the principal approach to creating such system.

Further optimization of the parameters of the radio frequency part is supposed to be carried out due to structural improvements - such as, for example, selection of distances between patches or change of dielectric material. The general approach - the construction of a complex system from relatively cheap
units of mass production, without the use of rare technologies and expensive materials, relying on affordable software and hardware - is supposed to be kept.

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References
[1] Ulaby F T, Moore R K and Fung A K 1982 Microwave Remote Sensing. Active and Passive vol 1,2,3 (Norwood, MA: Artech House)
[2] Shulgina E M, Rybakov Y V and Shchukin G G 1992 Proc. 3rd Specialists Meeting on MR and RS, Jan. 14-16, Colorado pp 50-8
[3] Alimenti F A et al 2006 Proc. 36th European Microwave Conf., Sept., Manchester, UK pp 1497-500
[4] Acevo-Herrera R et al 2010 Remote Sensing 2 pp 1662-79
[5] Chukhlantsev A and Shutko A 2008 30 Years of Research in to Microwave Radiometry of Vegetation Canopies at IRE RAS (Italy: MicroRad)
[6] Schmugge T J, Wang J R and Astar G 1988 IEEE Trans. Geosci. Sens. vol 26 5, pp 590-6
[7] Harrington R and Lawrence R W 1985 Proc. IGARSS pp 601-606
[8] Haarbrink R and Shutko A 2006 Proc. 2nd International Workshop on The Future of Remote Sensing, Oct. 17-18, Antwerp, Belgium pp 1-5
[9] Cappellin C et al 2015 9th European Conference on Antennas and Propagation (EuCAP) 13-17 April pp 1-5
[10] Bolsunov I A and Steriopolo Y A 1975 Antennas vol 21 (URSS: Svyaz) pp 81-5