CZECH TECHNICAL UNIVERSITY IN PRAGUE

DOCTORAL THESIS STATEMENT

Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Electromagnetic Field

Ing. Rastislav Galuščák

ADVANCED DESIGN OF REFLECTOR BASED ANTENNAS

Ph.D. Programme: Electrical Engineering and Information Technology

Branch of study Radioelectronics

Doctoral thesis statement for obtaining the academic title of "Doctor", abbreviated to "Ph.D."

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1. CURRENT SITUATION OF THE STUDIED PROBLEM

The problems of reflector based antenna are very extensive and dynamically evolving. Therefore, my descriptions in this section will be limited to the three areas that have been developed in the thesis.

1.1 Problems of primary feeds with circular polarization

Feeds are the driving source of electromagnetic field illumination in reflector antenna systems. For proper operational performance, reflector antennas should employ feeds with the following functional attributes:

a. Provide an illumination pattern that ensures good efficiency
b. Properly distribute energy onto the main- and sub-reflectors to meet side lobe suppression criteria
c. Exhibit low backward radiation to avoid interference between feed radiation and reflected radiation
d. Possess E- and H- plane phase centers concentrated as closely as possible to the parabolic dish focus
e. Deliver near homogeneous polarized energy with low crosspolarization components
f. Have good impedance match to the feed line over all specified operating frequencies to minimize line reflections
g. Posses sufficient bandwidth for the specified application
h. Be easily fabricated at low cost

These solutions are currently used to obtain circular polarization in waveguide lines:

- A waveguide polarizer equipped with a dielectric septum. It is particularly suitable for low-power-Rx applications where the losses in dielectric material and the low port-to-port isolation are not important.
- A waveguide polarizer with two perpendicular excitation probes, powered by a 90 degrees hybrid divider. The disadvantage of this arrangement is the necessity of using a hybrid power divider and the demands on its phase and amplitude accuracy.
- Waveguide polarizers with phasing elements. These are based on small changes in waveguide geometry. Thus, in a modified section, the desired phase shift is achieved. The disadvantage is low port-to-port isolation.
- A waveguide equipped with a septum polarizer. This devices has long been used in radar technology. The first simple sloped septum designs suffered from low axial ratio and port-to-port isolation. Improving the parameters of these polarizers was achieved by forming the septum into several steps. This solution includes dimensions that were first published by Chen and Tsandoulas [1]. Unfortunately this design also suffers from some asymmetry between azimuth and elevation planes. To improve the axial ratio and phase characteristics, some authors report using a series of tuning screws following the septum. Performance is controlled by adjusting the depth of these screws [2]. Others report controlling circularity with additional corner brackets and stiffeners employing a small ground plane [3]. Another solution, mounting a dielectric slab of Teflon behind the septum or by side wall dimension reduction was also described [4],[5]. These devices worked mostly on waveguides with a square cross-section. The development of numerical methods has allowed further optimization work using circular waveguide. Some of them

have been reported by Schennum and Skiver [2] and others [6],[7]. The author`s efforts in this area have been included in this thesis.

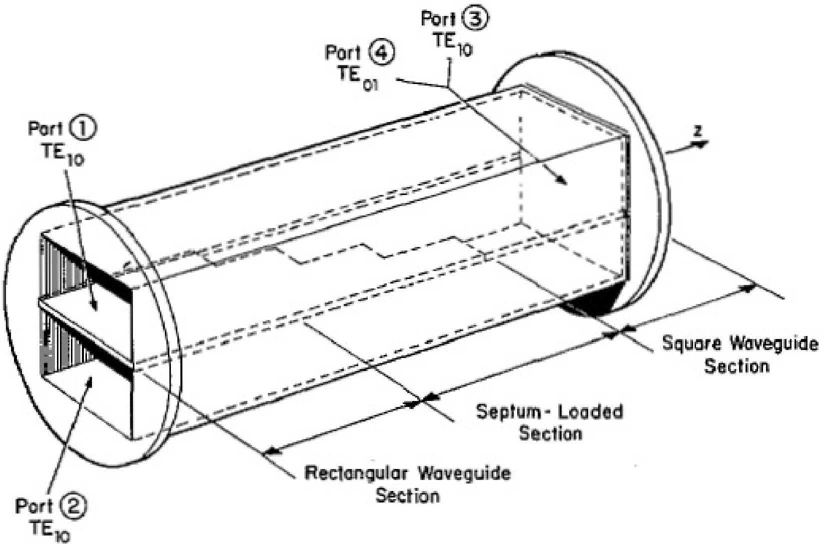

Fig. 1- Chen /Tsandoulas septum polarizer.

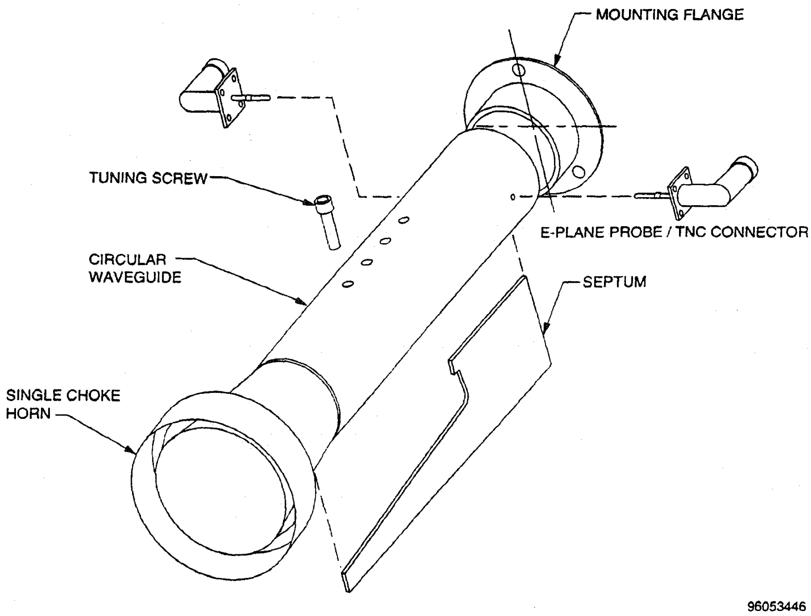

Fig. 2- Schennum / Skiver septum polarizer in a waveguide with circular cross-section.

1.2 Software for calculating antenna noise temperature

The possibility of calculating the antenna noise temperature is not offer by any electromagnetic field simulators. It is a very specific problem addressed mainly satellite antennas design.

Software suitable for calculating antenna noise temperature are:

a. Software „Kelvin sum“ developed in the 80`s by Miroslav Prochazka [8] The method used by this software assumes that the radiation pattern is axially symmetric. Taking into account its technical feasibility , it was high-quality software at that time. It works with DOS operating system (OS) and has no graphical interface. Antenna radiation patterns must be manually analyzed and the user must have a good understanding of antenna technology. Unfortunately, this method is less accurate.

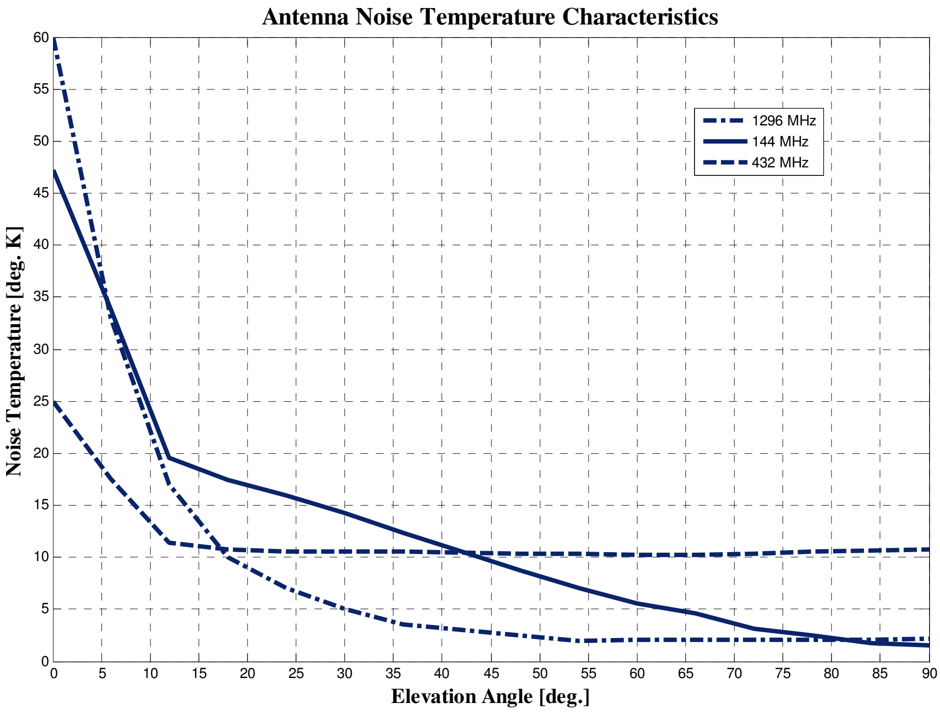

Fig. 3- Example of calculating the antenna noise temperature by „Kelvin sum“ software.

b. Software TANT, which is available on the Internet [9]. This software computes antenna noise temperature *T* and *G/T* ratio for antenna elevation angles from 0 to 90 degrees in steps of 5 degrees. The brightness temperature is defined for uniform sky 200 ° K and for Earth 1000 °K respectively. TANT software works only with the electromagnetic field simulator EZNEC. TANT software works also with OS DOS and has no graphical interface.

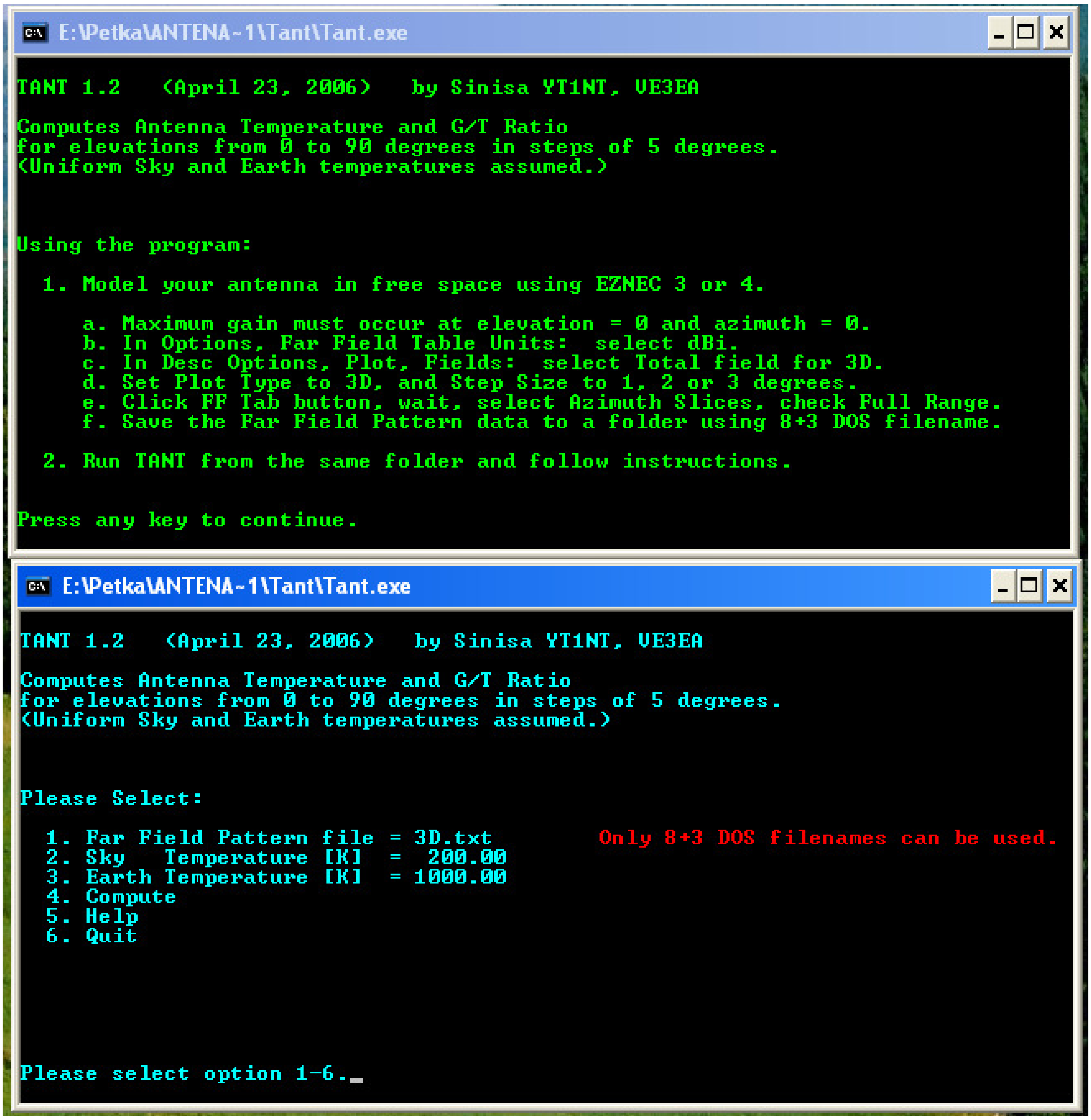

Fig. 4- TANT software dialog window in OS DOS.

This software did not meet my criteria of accuracy and ease of use. In my doctoral thesis I focused on, inter alia, the development of appropriate software that could be used with electromagnetic field simulators such as CST MW Studio and FEKO.

1.3 Calculation and measurement of S_{11}, S_{22} and S_{21} parameters of a prime- focus feed equipped with septum polarizer

In reflector antennas configured with a prime-focus feed, problems may arise with impedance match due to reflection from the center of the reflector. This problem must be taken into account especially in electrically small antennas where the prime focus feed is located relatively close to the reflector. Silver wrote about this in volume 12 of the Rad Lab Series. According to Silver [10], the reflection coefficient may be calculated by the equation:

$$\Gamma_r = \frac{G\lambda}{4\pi f} e^{-j(2kf)} \quad (1)$$

From (1), the magnitude of reflection coefficient is then given by formula:

$$|\Gamma_r| = G\lambda/4\pi f \quad (2)$$

Where: G is feed gain
λ is wavelength
f is focal length
$k = 2\pi/\lambda$

Silver published two solutions for improving prime-feed impedance matching. First, „**the vertex-plate matching technique**" is based on insertion of a phase plate above the parabolic reflector vertex. Moving the plate towards the feed causes the phase of the reflected signal to change until a shift of 180 degrees occurs.
The second solution described by Silver is „**the rotation of polarization technique**". The electric vector of the wave reflected by the parabolic reflector can be rotated through 90° with respect to the incident wave by means of a quarter-wave grating. This method demands technological adjustment of the reflector surface.
While the first method is suitable for circular polarization, the second method is suitable only for linear polarization.

Some reports concerning the impedance matching of his dual-mode circular polarized prime-focused feed was described by Turrin [11]. However to avoid this problem Turrin used off-set parabolic configuration.

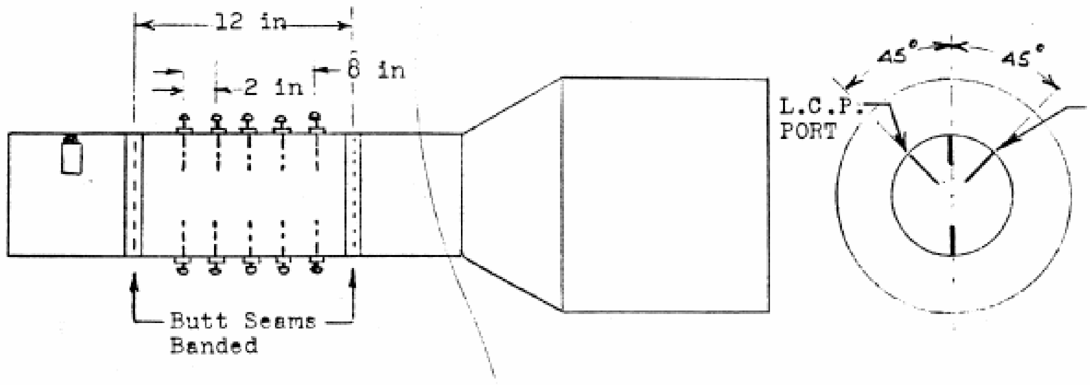

Fig. 5- Turrin 1296 MHz dual-mode feed for circular polarization.

While customizing the impedance matching technique has been well processed and documented by others, the influence on S parameters of prime-focus configured reflector antennas equipped with septum feed has been lacking. Therefore, there is a section of the thesis devoted to this problem.

2. AIMS OF THE DOCTORAL THESIS

The main goals of this work are:

2.1 To determine the optimum prime-focus antenna feed methodology for a given, fixed, dish reflector size, f/D ratio and frequency.

2.1.1 To define the antenna polarization properties and parameters of maximum gain, G/T ratio, impedance match (S_{11}), and port-to-port isolation (S_{21}).

2.1.2 To utilize modern electromagnetic simulation software to attain these objectives and compare and contrast the suitability of several types of numerical methods for a given application.

2.2 To analyze the influence of antenna noise temperature in low-noise reflector antenna systems.

2.2.1 To develop suitable antenna noise calculation software for these purposes.

2.3 To verify the theoretical solutions for these objectives using actual fabricated antennas and feeds.

2.3.1 To compare the calculated to the actual measured antenna parameters.

2.4 To evaluate the overall integrity and practicality of these antenna systems and propose accurate and useful conclusions about their application and performance.

3. WORKING METHODS

Thesis tasks were predominantly performed as independent projects used in amateur radio EME (Earth-Moon-Earth) microwave communications. This technique uses the moon as a passive reflector for earth-based stations that communicate via reflected microwaves. The findings in this thesis, however, are applicable to both terrestrial and extraterrestrial radio communications.

3.1 Project ***"Septum Feed Revisited"*** [12] This was the first project in cooperation with Czech Technical University in Prague. Contained in this work is a description of my efforts for improving and adapting a square cross-section feed with a septum polarizer. This feed was suitable for my relatively deep parabolic antenna (*f/D* ratio = 0.28).

Fig. 6 – Septum feed equipped with multi-collar rings.

3.2 Project ***„Optimization of prime-focus circular waveguide feed with septum polarization transformer for 1.296 GHz EME station"*** [13] This work describes our effort to design a circularly polarized 1.296 GHz feed with RHCP+LHCP patterns. Because electromagnetic waves reflected from the Moon changes its polarization sense, it is conventional to use a dual-port structure capable of receiving and transmitting both LH and RH polarizations simultaneously. Several factors must be considered:

- Return loss (S_{11}) and port to port isolation (S_{21})
- Efficiency of the septum polarizer
- Maintenance of good axial ratio
- Power handling capability

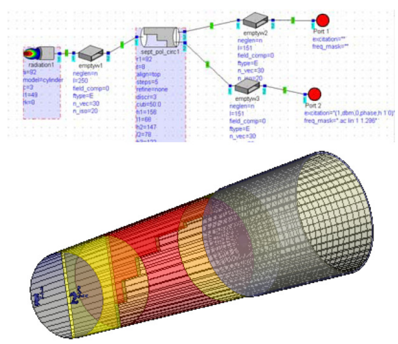

Fig. 7 - Simplified feed model for MMW analyses.

3.3 The septum polarizer-based feed was recalculated and optimized for a higher band at 2320 MHz. Also, further research was performed on the use of chokes to adapt and shape feed radiation patterns for an appropriate reflector size. This was discussed in the article ***"Prime-Focus Circular Waveguide Feed with Septum Polarization Transformer"*** published in DUBUS magazine [14].

Fig. 8 - Feeds for 13 cm band.

3.4 The problems associated with circular polarization and reflector antennas, including polarization loss analysis, were discussed and published in the DUBUS magazine article ***"Circular Polarization and Polarization Losses"*** [15].

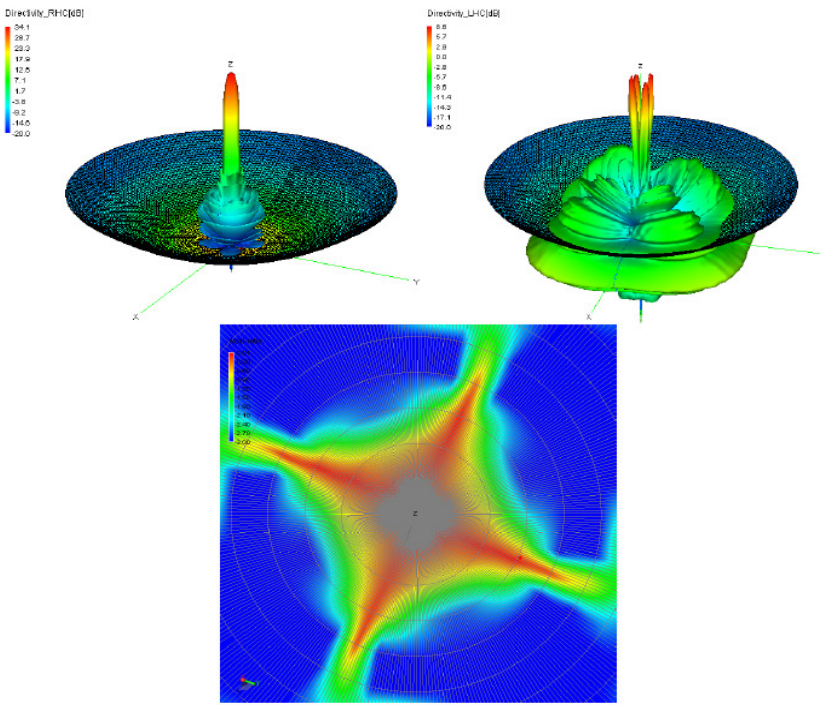

Fig. 9 - Computed co- (top-left) and crosspolarization (top-right) patterns and the axial ratio (bottom) of 20 λ dish with feed with square cross section equipped with a 4-step septum polarizer. Note maximums of crosspolarization in the direction of the feed diagonals.

3.5 Project ***"Big Dish"*** describes the challenging task of designing separate triple-band feeds for a 32 m KDDI Cassegrain parabolic antenna. This required a 23 cm LHCP/RHCP feed and a separate 70cm/2m linearly polarized feed. The article was published in Radioengineering Journal [16] and reprinted in DUBUS [17].

Fig. 10 - KDDI antenna equipped with 2m, 70cm and 23cm feeds.

3.6 In the previous work we analyzed noise properties of the transformed KDDI antenna system using Miroslav Prochazka`s software "Kelvin Sum." This software did not meet all of our criteria for future work, mainly regarding calculation precision and also was not compatible for use with electromagnetic simulation software (CST MW Studio, FEKO). Therefore, for our continuing research purposes we developed our own software, ***"Antenna Noise Temperature – Software Tools."*** The article describing its development was published in DUBUS magazine [18].

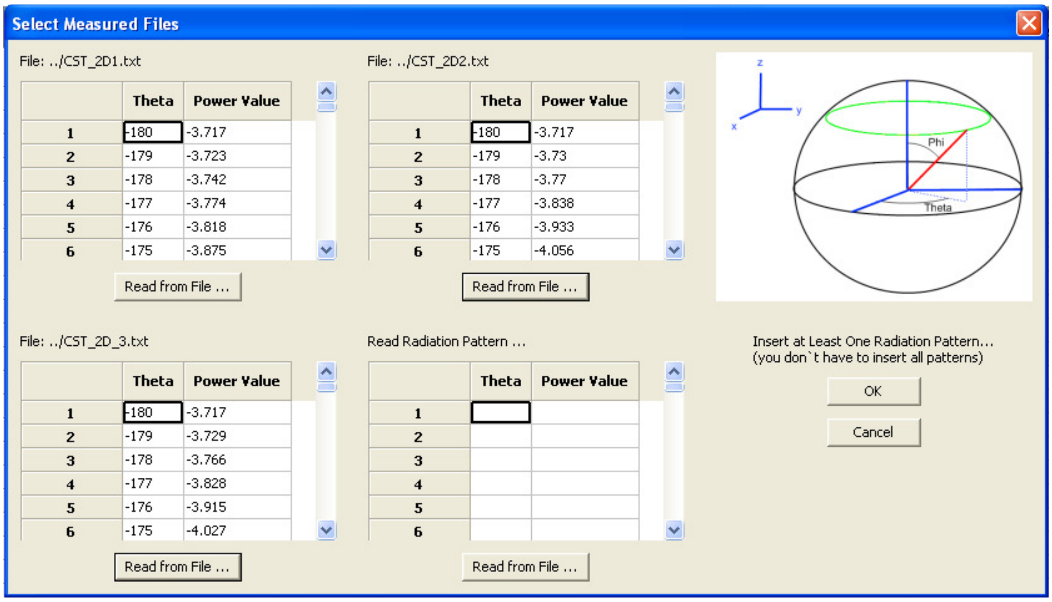

Fig. 11 - The ANTC data dialog window.

3.7 In the next work ***„Parabolic Antenna Noise Characteristic with Dual-Mode Feed“*** we perform noise analysis of a dual-mode (Potter) horn feed in prime-focus antenna configuration. In this project, practical application of our developed software, ANTC, was demonstrated. This article is currently unpublished, but will be submitted to Radioengineering Journal and DUBUS magazine for publication in the near future.

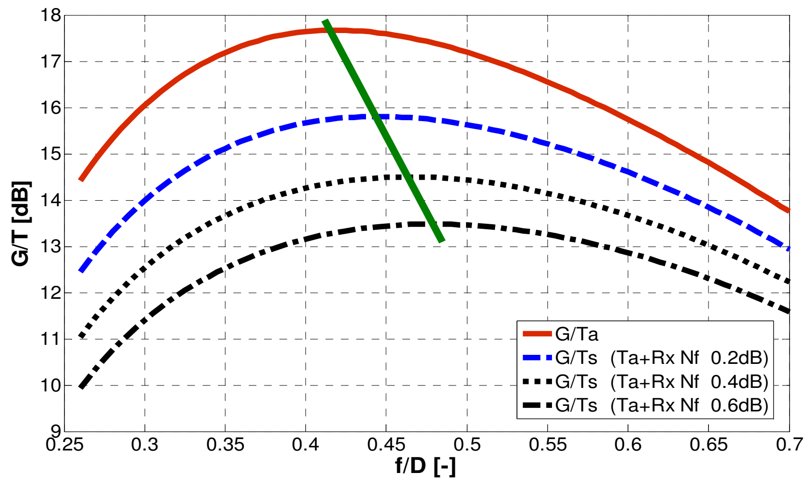

Fig. 12 - Antenna and system *G/T* ratio.

3.8 The project ***"Loop Feed with Enhanced Performance"*** addressed requirements for an easily fabricated feed for electrically small 23 and 13 cm band reflector antennas. Linear polarization was required for both bands. These articles covering analysis, design, measurement and practical experience were published in both Radioengineering and DUBUS magazine [19], [20].

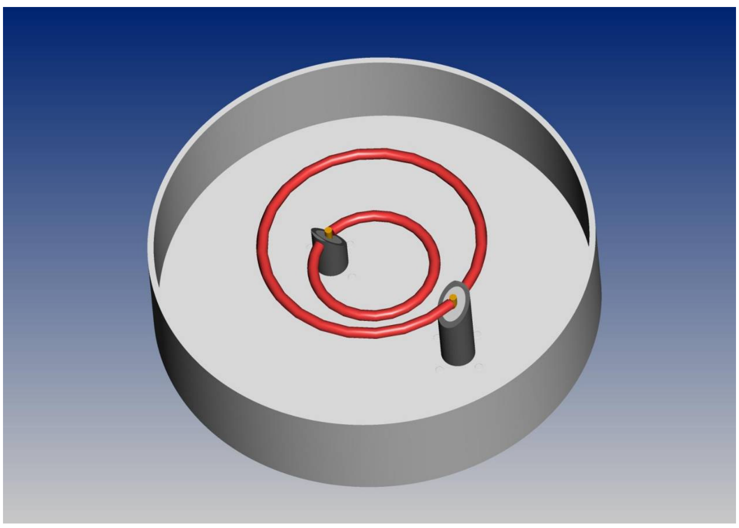

Fig. 13 - Dual band loop feed.

3.9 Another project was initiated to study *S* parameter variations of the circularly polarized septum feed installed on a parabolic reflector. This project was elaborated in cooperation with Pawlan Communication Copany. Articles documenting the findings of this collaboration were published in High Frequency Electronics magazine [21], [22] and in DUBUS magazine [23]. The following work is adapted from the articles "***Simulations and Measurements of a Prime Focus Dish with a Circular Septum Feed"*** and ***"Simulation and Measurement of the Effects of Reflections from a Prime Focus Dish back into a Circularly Polarized Feed"***

Fig. 14- Computer model (left) practical practical implementation (right)

4. RESULTS

The author had the opportunity to use both professionally- and academically-developed electromagnetic field simulation software programs for this research. Numerical methods such as Mode-Matching Technique (MICIAN), Physical Optics (ICARA), Finite Integration Technique (CST MW Studio, T-solver) and Multilevel Fast Multipole Method (FEKO, CST MW Studio, I-solver) were utilized. The use of the appropriate software for a particular task, including associated problems can be found in Chapter 4 of the thesis. Suitability of the applied numerical method can be divided between "feed" and "reflector" applications. Additionally, the combination of Finite Integration Technique and Multilevel Fast Multipole Method was used to calculate the radiation pattern of the entire antenna structure. Application of this method requires that the feed should operate in a "far field condition." The following selection tables show the suitability of a numerical method for each specific task.

Feed Parameter	Numerical Methods			
	MMT	PO	FIT	MLFMM
Radiation Pattern	+++	-	+++	++
S – Parameters	++	-	+++	+
Calculation speed	+++	-	+	++

Tab.1 - Suitability of the applied numerical method for “feed” applications

Parabolic Antenna Parameter	Numerical Methods			
	MMT	PO	FIT	MLFMM
Radiation Pattern	-	++	+++	+++
S – Parameters	-	-	+++	+
Calculation speed	-	+++	-	++
Remark			Considerably limited by computer RAM	

Tab.2 - Suitability of the applied numerical method for “reflector” applications

5. CONCLUSION

Extensive research on circularly polarized reflector antennas has been performed and documented. The author and his team have developed and fabricated antenna feeds equipped with a five-step septum polarizer for various microwave bands. Feeds outfitted with this polarizer deliver excellent performance in the areas of polarization efficiency, port-to-port isolation and impedance matching. Performance parameters of these devices were verified not only by measurement in an anechoic chamber but also by testing in the field.

The author and his team also had the oportunity to evaluate various fabrication technologies to construct working models of the feeds. For the 23 cm band, CNC machining technology combined with a demountable connection using screw fasteners to fix the septum polarizer inside the waveguide. For the 13 and 6 cm bands, laser cutting technology combined with welding and brazing were used. Measurement of a 6 cm septum feed suggested that tolerances of the septum dimensions must be less than $\lambda/500\ [mm]$ to achieve calculated parameters. If septum tolerances are not met, axial ratio degradation will occur. For a segment of the 1.6 cm band, this represents a tolerance of less than 0.032 mm. Due to this high demand for accurancy, special grinding and cutting technologies were used to fabricate feeds for this band.

• Directions for Future Work

The author`s research of reflector-based antennas is ongoing. Specifically, research to improve the Antenna Noise Temperature Calculator (ANTC) software and development of a new dual-band prime-focus feed for 70/13 cm bands. The developed dual-band feed (70/13 cm bands) is currently being tested in Athens. This device (Fig. 15) is intended for a parabolic reflector with a diameter of 6.4 m and *f/D* ratio of 0.4. Horizontal and vertical polarizations are available on the 70 cm band. The 13 cm band feed can operate with both right- and left-hand circular polarization. This feed was tested in an anechoic chamber owned by ERA Pardubice. The radiation patterns for both bands were measured and documented. See Fig. 16.

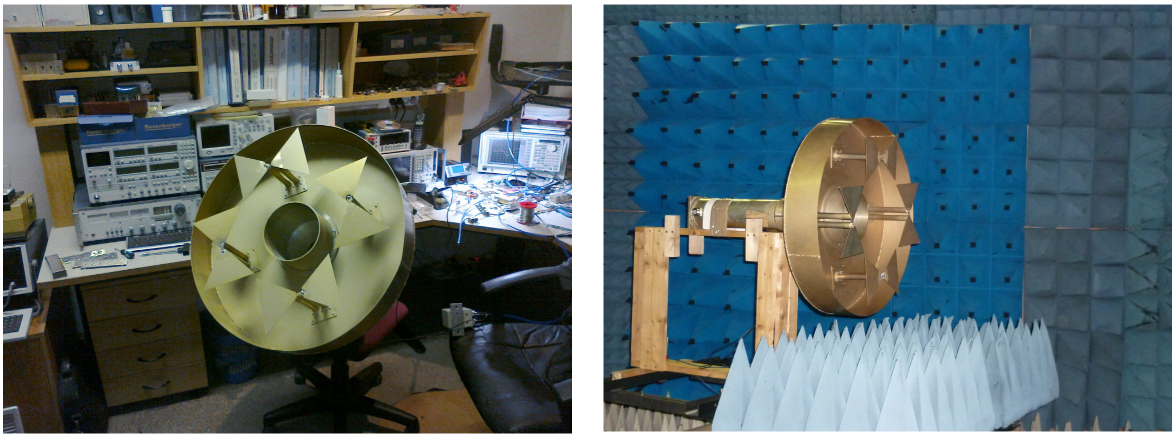

Fig.15 - Laboratory work on the dual band feed, laboratory (left) anechoic chamber (right).

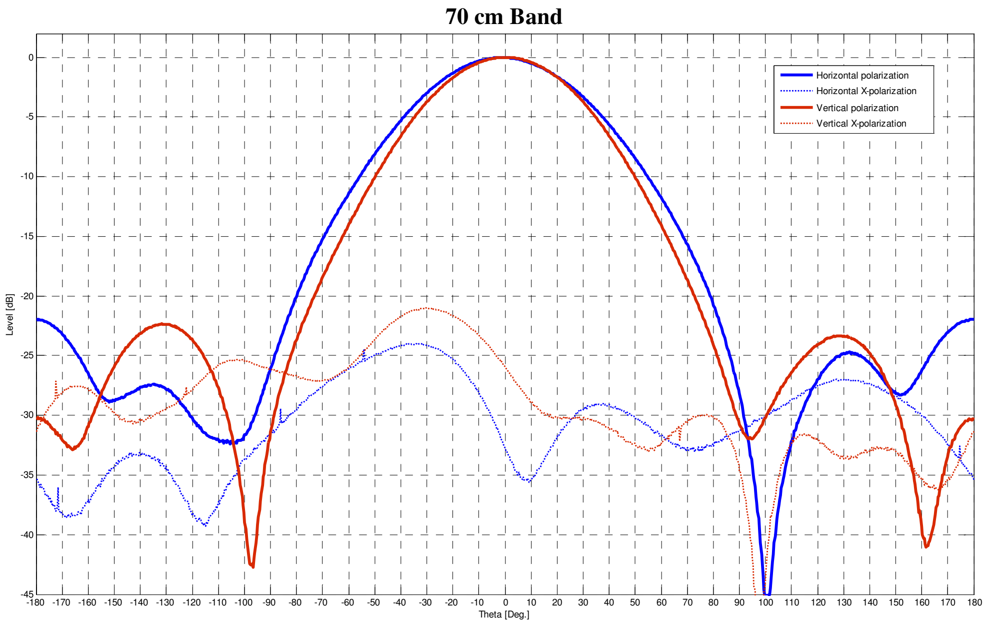

Fig. 16 - Measured radiation pattern of the dual band feed at 70 cm

List of literature used in the thesis statement

[1] Ming Hui Chen, G.N.Tsandoulas, *"A Wide-Band Square-Waveguide Array Polarizer."* IEEE Transaction on Antennas and Propagation, May 1973, pp. 389-391

[2] Gary. H. Schennum and Thomas M. Skiver, *"Antenna Feed Element for Low Circular Cross-Polarization"*, IEEE Publication 0-7803-3741-7/97, pp.135-150

[3] En-An Lee, *"A Low Cross-Polarization Circularity Polarized Spacecraft TC&R Antenna."*, IEEE Publication 0-7803-2009-3/94, pp. 914-917

[4] T. Ege, P. McAndrewas, *"Analysis of stepped septum polarizer*" Electronics Letters vol. 21, pp. 1166-1168, Nov. 1985

[5] N.D. Dand, S. Karpatis, D.J. Brain, *"A wide-bamd compact end-entry septum polarizer"* IEE ICAP Int. Conf. Digest, pp. 419-423, 1987

[6] J. Esteban, J.M. Rebollar, *"Field theory CAD of septum-OMT polarizers"* IEEE AP-S Int. Symp. Digest, pp. 2146-2149, July 1992

[7] R. Ihmels, U. Paziner, F. Arndrt, *"Field theory design of corrugated septum OMT*" IEEE MTT-S Digest, pp. 909-912, 1993

[8] Prochazka, Miroslav "*Kelvin Sum*"-software, Privately developed software program, 1999

[9] Tant, http://www.dual.co.yu/yu1cf/razno/news/news_item.asp?NewsID=6

[10] SILVER Samuel, *„Microwave Antenna Theory and Design",* MIT Rad Lab Series, Vol. 2, pp. 439-448, McGraw-Hill 1949.

[11] R.H. Turrin, *"Dual Mode Small-Aperture Antennas,"* IEEE Transactions on Antennas and Propagation, AP-15, March 1967, pp. 307-308

List of candidate`s works related to the thesis statement and doctoral thesis (authors contributed equally)

[12] Rastislav Galuscak , *„Septum Feed Revisited"*, DUBUS 4/2004, ISSN 1438-3705

[13] P. Hazdra, R. Galuscak, M. Mazanek, *„Optimization of prime-focus circular waveguide feed with septum polarization transformer for 1.296 GHz EME station",* COST 284 paper at EuCAP in Nice, 6-10 Nov. 2006

[14] Galuscak, Rastislav-OM6AA; Hazdra, Pavel; *„Prime-focus circular waveguide feed with septum polarization transformer"*, DUBUS, 1/2007, ISSN 1438-3705

[15] Galuscak Rastislav, Hazdra Pavel, *„Circular Polarization and Polarization Losses"*, DUBUS, 4/2006, ISSN 1438-3705

[16] R. Galuscak, M. Watanabe, P. Hazdra, S. Takeda, K. Seki, M. Prochazka, Y. Uchiyama *„Design of Primary Feeds for 32m KDDI Antenna System IBA-4 in Cassegrain Configuration*" Radioengineering , April 2008, Volume 17, Number 1

[17] R. Galuscak, M. Watanabe, P. Hazdra, S. Takeda, K. Seki, M. Prochazka, Y. Uchiyama *„Design of Primary Feeds for 32m KDDI Antenna System IBA-4 in Cassegrain Configuration*" DUBUS 4/2007, ISSN 1438-3705

[18] Rastislav GALUŠČÁK-OM6AA ,Petra GALUŠČÁKOVÁ, Miloš MAZÁNEK, Pavel HAZDRA, Martin MACÁŠ , *„Antenna Noise Temperature – Software Tools"* DUBUS 3/2009 pp.32-45 ISSN 1438-3705

[19] Galuscak Rastislav, Hazdra Pavel, *„Dual-band Loop Feed with Enhanced Performance*", Radioengineering, September 2008, Volume 17, Number 3

[20] Galuscak Rastislav, Hazdra Pavel, *„ Loop Feed With Enhanced Performance",* DUBUS 2/2008 ISSN 1438-3705

[21] PAWLAN J. and GALUŠČÁK R, *„Simulations and Measurements of a Circular Waveguide Septum Feed“,* High Frequency Electronics Magazine, July 2010, pp. 30–37.
[22] PAWLAN J. and GALUŠČÁK R., *„ Simulations and Measurements of a Prime Focus Dish with a Circular Septum Feed“.* High Frequency Electronics Magazine, August 2010, pp. 38 – 46.
[23] PAWLAN J. and GALUŠČÁK R, *„Simulation and Measurement of the Effects of Reflections from a Prime Focus Dish back into a Circularly Polarized Feed" ",* DUBUS 1/2011 ISSN 1438-3705

ANOTACE

V disertační práci byl proveden a zdokumentován rozsáhlý výzkum na kruhově polarizovaných reflektorových anténách. Autor a jeho tým vyvinul a vyrobil primární zářiče s pětistupňovou polarizační přepážkou pro různé mikrovlnná pásma. Vyvinuté primární zářiče vybavené tímto polarizátorem dosahují vynikajících parametrů co se týče čistoty polarizace, izolace mezi vstupními branami a impedančního přizpůsobení. Technické parametry těchto zařízení byly ověřeny nejen měřením v bezodrazové komoře, ale i testováním v praxi. Autor a jeho spolupracovníci měli také možnost porovnat různé výrobní technologie použité pro zhotovení funkčních modelů primárních zářičů.

Pro tento výzkum měl autor možnost používat jak profesionálně tak akademicky vyvinuté simulátory elektromagnetické pole. Byli využity numerické metody, jako jsou metoda sešívání vidů, (MICIAN), fyzikální optika (ICARA), metoda konečných integrálů FIT (CST MW Studio, T-řešič) a víceúrovňová rychlá multipólová metoda MLFMM (FEKO, CST MW Studio, I-řešič), Použití vhodného software pro jednotlivé úlohy, včetně souvisejících problémů je zdokumentováno v kapitole 4 a 5. Oblasti použití konkrétních numerických metod mohou být rozděleny na aplikace pro "primární zářiče“ a "reflektory". Pro výpočet vyzařovací charakteristiky celé antény bylo dále vyzkoušeno spojení technik metody konečných integrálů a víceúrovňové rychlé multipólové metody.

Pro návrh a analýzu nízkošumových přijímacích systému byl vyvinut program pro výpočet šumové teploty antén. Pro tento program byl navrhnut vlastní algoritmus pro otáčení vyzařovací charakteristiky antény v prostoru.
Na rozšíření tohoto programu se nadále pracuje. Pro modifikaci programu pro antény s velmi vysokým ziskem jsou přizvaní také Ph.D. studenti z Wroclavské Technické Univerzity.

Autor se v spolupráci s americkým partnerem také věnoval výzkumu vlivu odrazu signálu od parabolického reflektoru na *S* parametry tohoto zářiče pro středová uspořádaní, s primárním zářičem buzeným kruhovou polarizací.