Anomalies in NAVTEX Signal Reception in the Northern Adriatic: Discrepancies between Measurements and Propagation Models

Anomalije u prijemu NAVTEX signala na sjevernom Jadranu: odstupanja između mjerenja i modela propagacije

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Abstract

This research analyzes in detail the reception of NAVTEX signals in the northern Adriatic, revealing significant discrepancies between empirical observations and predictions of standard groundwave propagation models. The NAVTEX receiver at a fixed location on shore consistently failed to receive NAVTEX messages during daytime broadcasts from the Split and Piombino stations, despite being within their coverage area. At the same time, signals and messages from the nearest Mondolfo station were reliably received. Signal strength measurements confirmed that the signals from Split and Piombino stations were weak and unstable, while Mondolfo station provided a strong and stable signal. Comparison of these observations with the predictions of propagation models showed that the models predict signal strengths which should be sufficient for detection from all stations, including Split and Piombino. These findings indicate that current propagation models fail to accurately capture complex environmental factors or potential transmitter performance issues. It is concluded that these models cannot be reliably used to predict NAVTEX coverage in such complex maritime environments, which has critical implications for maritime safety due to the inability to receive Maritime Safety Information (MSI) via the NAVTEX system.

KEY WORDS
NAVTEX
RF signal strength
RF spectral analysis
groundwave propagation models

Sažetak

Ovaj rad detaljno analizira prijem NAVTEX signala na sjevernom Jadranu, otkrivajući značajna odstupanja između empirijskih opažanja i predviđanja standardnih modela propagacije površinskog vala. NAVTEX prijemnik na fiksnoj lokaciji na obali dosljedno nije uspijevao primiti NAVTEX poruke tijekom dnevnih emisija s postaja Split i Piombino unatoč tome što se nalazio unutar njihova područja pokrivanja. Istovremeno su signali i poruke s najbliže postaje Mondolfo pouzdano primani. Mjerenja jačine signala potvrdila su da su signali s postaja Split i Piombino bili slabi i nestabilni, dok je postaja Mondolfo pružala snažan i stabilan signal. Usporedba ovih opažanja s predviđanjima modela širenja signala pokazala je da modeli predviđaju jačine signala koje bi trebale biti dovoljne za detekciju sa svih postaja, uključujući Split i Piombino. Ovi rezultati upućuju na to da trenutni modeli širenja signala ne uspijevaju točno obuhvatiti složene čimbenike okoliša ili potencijalne probleme u radu odašiljača. Zaključuje se da se ti modeli ne mogu pouzdano koristiti za predviđanje pokrivenosti NAVTEX sustavom u tako složenim morskim okruženjima, što ima kritične implikacije za sigurnost plovidbe zbog nemogućnosti primanja Pomorskih sigurnosnih informacija (MSI) putem NAVTEX sustava.

KLJUČNE RIJEČI
NAVTEX
jačina RF signala
spektralna analiza RF signala
modeli širenja površinskim valom

1. INTRODUCTION / *Uvod*

The NAVTEX system is part of a wider worldwide MSI coordination, including the World Navigational Warning Service (WWNWS) and the World Met-Ocean Information and Warning Service (WWMIWS), which divide the world into 21 NAVAREA/METAREA areas. The NAVTEX system is also a key component of the Global Maritime Distress and Safety System (GMDSS), and for many years a NAVTEX receiver was mandatory on ships subject to the provisions of the International Convention for the Safety of Life at Sea (SOLAS). The NAVTEX is an international narrow-band direct-printing (NBDP) system for transmitting MSI and search and rescue (SAR) related information from coast stations, developed to provide a simple and automated way of receiving this information on ships navigating within their coverage area. The system uses the international frequency of 518 kHz to transmit messages in English, while on frequencies of 490 kHz and 4209.5 kHz messages are most often transmitted in the national languages. Within each NAVAREA/METAREA, there can be a maximum of 24 NAVTEX stations (on each frequency), designated by the letters A to X. In order to prevent interference of NAVTEX station signals,

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their broadcasting schedule is determined so that two or more stations do not overlap in time, i.e. on a daily basis in alphabetical order, each station broadcasts for a maximum of 10 minutes every 4 hours. Additionally, each NAVTEX station transmits at a minimum power to cover an area of approximately 400 NM, and stations in adjacent NAVAREA/METAREAs with the same designations are at greater distances from each other. Within an allocated time slot, NAVTEX messages are transmitted in a standardized format and with a certain priority. NAVTEX receivers automatically receive these messages, and users can filter them by range, type and station [1]. One of such receivers is located at the University of Rijeka, Faculty of Maritime Studies, Croatia (Northern Adriatic) for the purpose of teaching and training students and seafarers. During months of 24-hour operation of this device, unusual reception or non-reception of NAVTEX signals from certain NAVTEX stations was observed. The most interesting observation is certainly the inability to receive NAVTEX signals and messages during daytime (and often nighttime) broadcasts of the Split station, whose transmitting center is located on the island of Hvar, Croatia. On the other hand, nighttime broadcasts of very distant stations from other NAVAREA/METAREAs were recorded during the same period.

Reviewing previous scientific research on the subject of NAVTEX, no similar problems of propagation and reception of NAVTEX signals were recorded. In general, there are very few publications which study the NAVTEX system and receiver. Thus, the implementation of an Android application that displays NAVTEX messages on a Google map in order to help mariners in safer navigation is described in [2]. In [3], six different deep learning models based on Bi-LSTM Conditional Random Field (CRF) architecture were analyzed for semantic classification of NAVTEX messages to enable their automatic processing and conversion into machine-readable Common Maritime Data Structure (CMDS) for safe navigation of smart ships. The application of deep and machine learning for the automatic classification of NAVTEX messages was also presented by the authors in papers [4, 5, 6]. Furthermore, the design and implementation of an exciter device for the transmission of meteorological fax charts and NAVTEX messages is described in [7], emphasizing the advantages of miniaturization, low energy consumption and high reliability with experimental confirmation of the device's functionality. The authors in [8] examined the possibilities of data transmission from external hydro-meteorological sensors via the Automatic Identification System (AIS), proposing a model in which data from ship, including NAVTEX, and coast are compared in order to increase the accuracy of meteorological information at sea, which contributes to safer navigation and reduction of risks for the crew and vessels.

Furthermore, the analysis of NAVTEX messages from a navigational safety perspective was presented in [9], where the authors examined NAVTEX messages broadcast from the Antalya station for the Mediterranean region between 2019 and 2022, concluding that studying the trends of NAVTEX messages can provide significant data about the regional navigational risks. It is noteworthy that none of the aforementioned publications have addressed the problem of NAVTEX signal propagation or signal reception anomalies, which is the central topic of this paper.

On the other hand, the groundwave propagation, which is the main daytime propagation mechanism of NAVTEX signals, has been researched countless times, and there are a handbook and a recommendation of the International Telecommunication Union (ITU) for predicting the groundwave propagation [10, 11]. In this ITU handbook, there is also an overview of the groundwave theory, so the readers are recommended to review all the references contained within it, in order to become familiar with this topic. Recent research has further advanced groundwave propagation modeling, particularly for maritime radio navigation applications. In [12], the authors developed an Atmospheric and Ground Wave Delay Factor (AGDF) approach for the medium frequency Ranging Mode (MF R-Mode) radionavigation system, computing and mapping the ground wave propagation delay in 2D for MF R-Mode transmitters in the Baltic Sea. Their results demonstrated that the proposed AGDF approach provides accurate corrections of ground wave propagation delays within the performance requirements, and highlighted that the largest source of error in the prediction is the inaccuracy of the underlying ITU recommendation World Atlas of Ground Conductivities. Building on this work, the same research group presented in [13] a model for ground wave propagation across sea ice for radio navigation applications, using Earth observation data from the E.U. Copernicus services to compute the impact of varying sea-ice conditions on signal propagation. Their simulation results for a real-world scenario in the Gulf of St. Lawrence showed that the signal propagation delay caused by sea ice can lie in the order of 20 ns with respect to sea water, which is significant for positioning accuracy. These studies are relevant to the present research as they demonstrate the sensitivity of medium frequency groundwave signals to environmental conditions and the limitations of static propagation models in dynamic maritime environments. Moreover, the ITU recommendation describes an integral software procedure for calculating groundwave propagation at frequencies from 10 kHz to 30 MHz, considering the electrical characteristics of the ground and mixed paths, in order to precisely determine the path loss and field strength. The implementation of the software procedure for homogeneous trajectories (Annex 1 of the ITU recommendation) in the MATLAB software is available on the ITU website [14]. For inhomogeneous trajectories (Annex 2 of the ITU recommendation) there is a MATLAB tool described in [15]. This scientific paper presents the development and application of a virtual tool for predicting groundwave field strengths in digital radio systems on medium and short waves, based on the Millington method and analytical-numerical models, which enables precise simulation of path losses in complex propagation scenarios over different types of terrain and land-sea transitions, with validation of results through characteristic examples. Furthermore, an overview of groundwave propagation modeling and simulation strategies as well as path loss prediction tools in radio communication and radar systems, including the ITU recommendation, is given in paper [16]. An integrated MATLAB-based simulator that combines the Method of Moments (MoM) and Split-Step Parabolic Equation (SSPE) methods for predicting the groundwave field strength is introduced in [17]. This simulator enables comparison of different numerical approaches, modeling of uneven terrain and atmospheric effects. There is also a MATLAB-based tool that uses the Finite Element Method and parabolic equation (FEMPE) for precise calculation of signal losses along uneven terrains with different electrical characteristics, which is presented in [18]. The tool enables the modeling of groundwave propagation through an inhomogeneous atmosphere at frequencies from 10 kHz to 30 MHz, including the previously mentioned Millington method for mixed paths.

The northern Adriatic region presents a particularly challenging environment for radio wave propagation at medium frequencies. The area is characterized by a semi-enclosed sea basin surrounded by complex coastal topography, including the Dinaric Alps along the Croatian coast, the Apennine mountain range on the Italian side, and numerous islands in the Croatian archipelago. These geographical features create complex mixed land-sea propagation paths for groundwave signals, where the signal must traverse surfaces with significantly different electrical characteristics: from highly conductive seawater to poorly conductive dry coastal land and mountainous terrain. Each transition between different surface types introduces additional propagation losses and phase shifts, as described by the Millington method for mixed paths. Furthermore, the Adriatic region is known for anomalous atmospheric propagation conditions. Previous research conducted in the same geographical area at the northern Adriatic has documented the occurrence of enhanced, over-the-horizon signal propagation caused by atmospheric refraction effects, including ducting, superrefraction, and subrefraction [19]. Studies have also shown that trapping and superrefractive conditions most commonly occur in the Po Valley and low-lying coastal areas of the northern Adriatic [20]. While these anomalous propagation effects are more pronounced at VHF and higher frequencies, the complex atmospheric conditions and coastal terrain also influence groundwave propagation at MF frequencies, contributing to signal variability and potential fading. Additionally, the electromagnetic noise environment at MF frequencies, as characterized by ITU's recommendation [21], includes contributions from atmospheric noise due to lightning, which varies seasonally and diurnally, and man-made noise from industrial and urban sources along the densely populated coastal areas of Italy and Croatia.

Given all the above, the main objective of this paper is to analyze the reception of NAVTEX messages and signals by measuring the signal strength in the time slots of daytime broadcasts of NAVTEX stations. Additionally, using the available software tools, groundwave propagation of these daytime broadcasts will be modeled, simulated and compared with signal strength measurements. This implicitly poses the crucial validation (or invalidation) of widely accepted radio propagation models against real-world data, within the critical context of maritime safety.

2. METHODOLOGY / Metodologija

For the purposes of this research, i.e. for receiving NAVTEX signals and messages in real time, a SAILOR 6390 NAVTEX Receiver was used, which can receive NAVTEX messages on all three previously mentioned frequencies and store up to 2000 messages per each frequency [22]. This NAVTEX receiver is located in the NAVAREA/METAREA III area and, according to the available data, is within the signal range of 3 NAVTEX stations. Data on these stations can be found in Table 1, while the positions, coverage areas and distances from the receivers are shown in Figure 1 [23].

Table 1 NAVTEX stations covering receiver

Tablica 1 NAVTEX postaje u dometu prijemnika

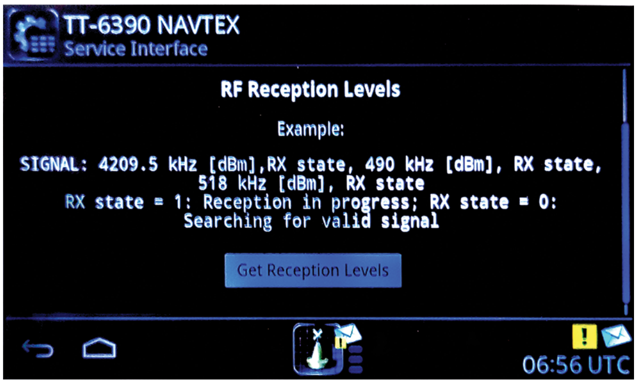
Station name	Station ID	Frequency	Range	Transmission times (UTC)					
Mondolfo	E	490 kHz	320 NM	0:40	4:40	8:40	12:40	16:40	20:40
	U	518 kHz		3:20	7:20	11:20	15:20	19:20	23:20
Piombino	N	490 kHz	320 NM	2:10	6:10	10:10	14:10	18:10	22:10
Split	F	490 kHz	200 NM	0:50	4:50	8:50	12:50	16:50	20:50
	Q	518 kHz		2:40	6:40	10:40	14:40	18:40	22:40

Figure 1 NAVTEX stations' positions, coverage areas and distance from receiver. The map was created using version 7.3.6.10201 of Google Earth Pro software, which is available for free download at https://www.google.com/earth/about/versions/#download-pro.

Slika 1. Položaji NAVTEX postaja, područja pokrivanja i udaljenost od prijemnika. Karta je izrađena korištenjem verzijom 7.3.6.10201 softvera Google Earth Pro koji je dostupan za besplatno preuzimanje na poveznici: https://www.google.com/earth/about/versions/#download-pro.

The NAVTEX receiver is connected to an active NAVTEX antenna placed at an altitude of 36 m, as well as to the SAILOR 6004 Control Panel. The NAVTEX receiver and the associated control panel were installed at the Faculty of Maritime Studies in 2020. At the time of measurements, the equipment was approximately 5 years old. The receiver, control panel, active NAVTEX antenna and the coaxial cable connecting the antenna to the receiver were all in good operational condition, with no visible signs of physical damage, corrosion, or water penetration to the cable. Regular maintenance, testing and visual inspections of the equipment are performed as part of the educational activities. The reliable and stable reception from the Mondolfo station throughout the entire observation period further confirms the proper functioning of the receiving system. For the purposes of analyzing the reception of NAVTEX signals and messages, the NAVTEX receiver was set to manual mode (without the ability to filter range, stations and messages) and all received NAVTEX messages were displayed on the Control Panel screen, in the Navtex application, during several months of operation. After that, the USB storage device was used to store the database of all messages through the Control Panel in a comma separated values (CSV) file.

In addition to collecting the received NAVTEX messages, it was necessary to measure the signal strength in known daytime intervals of the NAVTEX stations in range. For this task, the Service Interface on the Control Panel was used, where the RF Reception Levels option was selected. After startup, RF signal strength measurements at all three frequencies were displayed on the Control Panel screen. In each line, the signal level in dBm was displayed, indicating whether reception was in progress and/or searching for a valid signal for 4209.5 kHz, 490 kHz and 518 kHz, respectively (Figure 2).



SIGNAL: 4209.5 kHz [dBm],RX state, 490 kHz [dBm], RX state, 518 kHz [dBm], RX state
RX state = 1: Reception in progress; RX state = 0: Searching for valid signal

Figure 2 NAVTEX receiver RF Reception Levels
Slika 2. RF razine prijema NAVTEX prijemnika

In order to verify the validity of NAVTEX receiver measurements and to assess its receiving sensitivity, additional measurements were performed using a RIGOL DSA705 spectrum analyzer with a passive LF/MF/HF antenna [24].

3. MEASUREMENT RESULTS / *Rezultati mjerenja*

After collecting NAVTEX messages, their analysis followed. The period from June 1 to June 30, 2025 was analyzed. A total of 1027 NAVTEX messages were stored during this period:

- 775 at 518 kHz;
- 247 at 490 kHz;
- 5 at 4209.5 kHz.

As might be expected, given the manual reception mode, most NAVTEX messages were received during nighttime broadcasts from both nearby and distant stations. However, as already emphasized, only the stations from Table 1 are of interest in this research. Thus, a total of 294 NAVTEX messages were received from the Mondolfo station, of which 152 on 518 kHz and 142 on 490 kHz during all broadcast times (both daytime and nighttime). A total of 43 NAVTEX messages were received from the Split station, of which 25 on 518 kHz and 18 on 490 kHz. Additional analysis of the messages received from the Split station revealed that 20 messages were received at 22:40 UTC, 4 messages at 2:40 UTC and 1 message at 18:40 UTC (20:40 local time) on 518 kHz. The presence of a single message from Split station at 18:40 UTC (which is still daytime in June) on 518 kHz is an important outlier. This may indicate a very marginal signal that occasionally manages to "get through", or a favorable transient propagation event. However, its rarity highlights the general and ongoing lack of reliable daytime reception from Split station. Analysis of the messages received on 490 kHz revealed that 11 messages were received at 0:50 UTC and 7 at 20:50 UTC. Finally, only 7 messages were received from the Piombino station, all at 2:10 UTC.

Since the Piombino station does not transmit on an international frequency, RF Reception Levels measurements were conducted exclusively on 490 kHz over several days in the period from 8:40 to 13:00 UTC. Figures 3 - 5 show screenshots of measurements conducted on June 13, 2025 at 5 time slots of the observed NAVTEX stations: two from Mondolfo and Split and one from Piombino. Figure 3 presents two consecutive screenshots of the RF Reception Levels display on the SAILOR 6004 Control Panel, captured during the Mondolfo station's daytime broadcast time slots at 8:40 UTC and 12:40 UTC on June 13, 2025. The display provides real-time signal level readings at all three NAVTEX frequencies (4209.5 kHz, 490 kHz, and 518 kHz), presented in three columns. Each row displays the measured signal strength in dBm, along with the reception status indicator showing whether the receiver is actively searching for, or has locked onto, a valid NAVTEX signal. In both measurements, the 490 kHz column shows a stable signal level of -66 dBm from the Mondolfo station, which is well above the minimum signal strength required for successful NAVTEX message reception. The stability of the signal is evidenced by the consistent reading across both time slots, indicating a reliable groundwave propagation path between the Mondolfo transmitter and the receiving location. The bottom status bar of the Control Panel display shows the NAVTEX message reception indicators; in both screenshots, the lowest green light (corresponding to 490 kHz) is illuminated, confirming that the receiver has successfully detected the signal, locked onto the phasing sequence, and is actively demodulating and decoding NAVTEX messages from the Mondolfo station. In contrast, the 4209.5 kHz and 518 kHz columns show no significant signal, which is expected as there are no nearby stations transmitting on these frequencies during these time periods.

On the other hand, Figure 4 shows two measurements of the received signal from the Split station, and both measurements show that there is no stable signal at 490 kHz (varies between -85 dBm and -80 dBm) and there is no successful detection, demodulation and decoding of NAVTEX messages. Additionally, in both measurements, the bottom bar

Table 2 RF Reception Levels measurements on June 13, 2025 (490 kHz)

Tablica 2. Mjerenja RF razina prijema 13. lipnja 2025. (490 kHz)

Station	Time slot (UTC)	Signal level (dBm)	Signal stability	NAVTEX message decoded	Reception indicator
Mondolfo (E)	8:40	-66	Stable	Yes	Green (active)
Mondolfo (E)	12:40	-66	Stable	Yes	Green (active)
Split (F)	8:50	-85 to -80	Unstable	No	Inactive
Split (F)	12:50	-83 to -80	Unstable	No	Inactive
Piombino (N)	10:10	-83 to -79	Unstable	No	Inactive

does not show the indicator of receiving a NAVTEX message at 490 kHz. This signal instability suggests the presence of fading or rapid signal fluctuations, which is extremely detrimental to digital communication systems such as NAVTEX. Even if the average signal strength occasionally reaches detection levels, the lack of stability means that the signal to noise ratio (SNR) is probably insufficient for locking to the phasing signal. The same observations are visible in Figure 5, which shows the measurement of the received signal from the Piombino station. The same pattern was repeated over several days of measurements at the same time periods.

Table 2 summarizes the key measurement data from the RF Reception Levels screen of the SAILOR 6004 Control Panel.

In order to verify that the observed NAVTEX stations Split and Piombino actually broadcasted during the specified periods, it was necessary to search the archive of NAVTEX messages. However, there is no archive available for the Piombino station, as is the case with the Split station. Thus, broadcasted messages from the observed time periods were found on the website of the Split station's owner. The headers of these messages are:

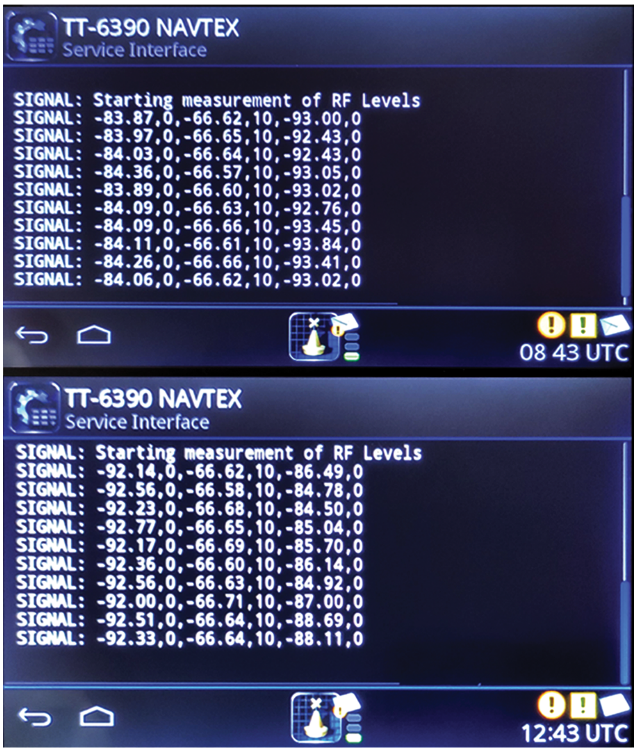
- FE82 / 13.6.2025. 12:56:32 / 490 kHz
- FA52 / 13.6.2025. 12:53:18 / 490 kHz
- FA50 / 13.6.2025. 12:52:00 / 490 kHz
- FA46 / 13.6.2025. 12:50:51 / 490 kHz
- FE81 / 13.6.2025. 8:56:44 / 490 kHz
- FA52 / 13.6.2025. 8:53:18 / 490 kHz
- FA50 / 13.6.2025. 8:51:59 / 490 kHz
- FA46 / 13.6.2025. 8:50:51 / 490 kHz

Therefore, from the aforementioned archive, it can be concluded that the Split station broadcasts during daytime hours, but the NAVTEX signal is not strong enough for the receiver to successfully detect it and decode NAVTEX messages.

Additional measurements with spectrum analyzer were performed during the daytime broadcasts of the Mondolfo and Split stations on 490 kHz. Although the RIGOL DSA705 spectrum analyzer supports screen capture and data transfer to a PC, the spectral measurements presented in Figure 6 were captured in real-time during the coordinated NAVTEX signal measurement campaign. Therefore, the screenshots from the analyzer's display are presented as they were recorded during the actual measurement sessions.

The upper panel of Figure 6 shows the spectrum captured during the Mondolfo station's broadcast, and the lower panel shows the spectrum captured during the Split station's broadcast. In the upper panel (Mondolfo station), a distinct spectral peak is clearly visible at 490 kHz, rising approximately 20 dB above the noise floor. The peak is well-defined and narrow, consistent with the expected Narrow-Band Direct Printing (NBDP) modulation characteristics of the NAVTEX signal, which uses 100 baud FSK modulation with a 170 Hz frequency shift. The signal-to-noise ratio observed at the spectrum analyzer is sufficient to confirm the presence of a strong Mondolfo signal at the receiving location. The measured signal level of approximately -80 dBm is notably lower than the -66 dBm measured by the NAVTEX receiver with its active antenna, which is consistent with the expected performance difference between the passive antenna connected to the spectrum analyzer and the active NAVTEX antenna connected to the professional receiver.

In the lower panel (Split station), no discernible spectral peak is visible at 490 kHz; the trace at this frequency is indistinguishable from the background noise floor. This confirms that the signal from the Split station is either not reaching the receiving location or is arriving at a level below the noise floor of the measurement system. The comparison between the two panels provides compelling independent verification of the NAVTEX receiver measurements: the Mondolfo signal is clearly present and detectable, while the Split signal is absent or below the detection threshold of even a dedicated spectrum analyzer.

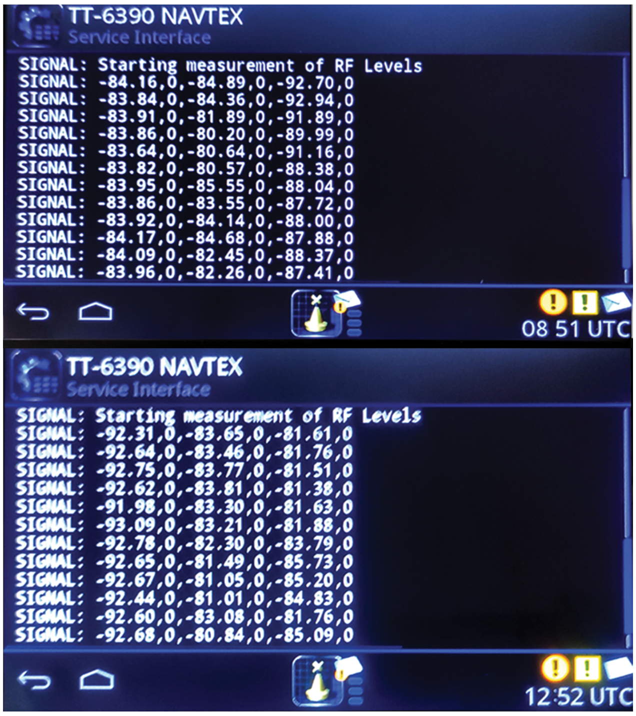


```
SIGNAL: Starting measurement of RF Levels
SIGNAL: -83.87,0,-66.62,10,-93.00,0
SIGNAL: -83.97,0,-66.65,10,-92.43,0
SIGNAL: -84.03,0,-66.64,10,-92.43,0
SIGNAL: -84.36,0,-66.57,10,-93.05,0
SIGNAL: -83.89,0,-66.60,10,-93.02,0
SIGNAL: -84.09,0,-66.63,10,-92.76,0
SIGNAL: -84.09,0,-66.66,10,-93.45,0
SIGNAL: -84.11,0,-66.61,10,-93.84,0
SIGNAL: -84.26,0,-66.66,10,-93.41,0
SIGNAL: -84.06,0,-66.62,10,-93.02,0
```

```
SIGNAL: Starting measurement of RF Levels
SIGNAL: -92.14,0,-66.62,10,-86.49,0
SIGNAL: -92.56,0,-66.58,10,-84.78,0
SIGNAL: -92.23,0,-66.68,10,-84.50,0
SIGNAL: -92.77,0,-66.65,10,-85.04,0
SIGNAL: -92.17,0,-66.69,10,-85.70,0
SIGNAL: -92.36,0,-66.60,10,-86.14,0
SIGNAL: -92.56,0,-66.63,10,-84.92,0
SIGNAL: -92.00,0,-66.71,10,-87.00,0
SIGNAL: -92.51,0,-66.64,10,-88.69,0
SIGNAL: -92.33,0,-66.64,10,-88.11,0
```

Figure 3 RF Reception Levels from Mondolfo station

Slika 3. RF razine prijema s postaje Mondolfo



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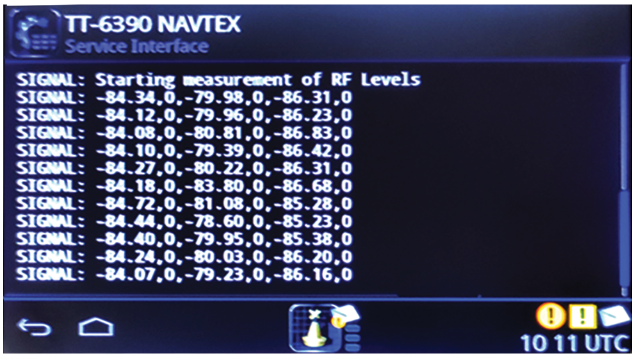
SIGNAL: Starting measurement of RF Levels
SIGNAL: -84.16,0,-84.89,0,-92.70,0
SIGNAL: -83.84,0,-84.36,0,-92.94,0
SIGNAL: -83.91,0,-81.89,0,-91.89,0
SIGNAL: -83.86,0,-80.20,0,-89.99,0
SIGNAL: -83.64,0,-80.64,0,-91.16,0
SIGNAL: -83.82,0,-80.57,0,-88.38,0
SIGNAL: -83.95,0,-85.55,0,-88.04,0
SIGNAL: -83.86,0,-83.55,0,-87.72,0
SIGNAL: -83.92,0,-84.14,0,-88.00,0
SIGNAL: -84.17,0,-84.68,0,-87.88,0
SIGNAL: -84.09,0,-82.45,0,-88.37,0
SIGNAL: -83.96,0,-82.26,0,-87.41,0
```

```
SIGNAL: Starting measurement of RF Levels
SIGNAL: -92.31,0,-83.65,0,-81.61,0
SIGNAL: -92.64,0,-83.46,0,-81.76,0
SIGNAL: -92.75,0,-83.77,0,-81.51,0
SIGNAL: -92.62,0,-83.81,0,-81.38,0
SIGNAL: -91.98,0,-83.30,0,-81.63,0
SIGNAL: -93.09,0,-83.21,0,-81.88,0
SIGNAL: -92.78,0,-82.30,0,-83.79,0
SIGNAL: -92.65,0,-81.49,0,-85.73,0
SIGNAL: -92.67,0,-81.05,0,-85.20,0
SIGNAL: -92.44,0,-81.01,0,-84.83,0
SIGNAL: -92.60,0,-83.08,0,-81.76,0
SIGNAL: -92.68,0,-80.84,0,-85.09,0
```

Figure 4 RF Reception Levels from Split station
Slika 4. RF razine prijema s postaje Split



```
SIGNAL: Starting measurement of RF Levels
SIGNAL: -84.34,0,-79.98,0,-86.31,0
SIGNAL: -84.12,0,-79.96,0,-86.23,0
SIGNAL: -84.08,0,-80.81,0,-86.83,0
SIGNAL: -84.10,0,-79.39,0,-86.42,0
SIGNAL: -84.27,0,-80.22,0,-86.31,0
SIGNAL: -84.18,0,-83.80,0,-86.68,0
SIGNAL: -84.72,0,-81.08,0,-85.28,0
SIGNAL: -84.44,0,-78.60,0,-85.23,0
SIGNAL: -84.40,0,-79.95,0,-85.38,0
SIGNAL: -84.24,0,-80.03,0,-86.20,0
SIGNAL: -84.07,0,-79.23,0,-86.16,0
```

Figure 5 RF Reception Levels from Piombino station
Slika 5. RF razine prijema s postaje Piombino

Figure 6 Spectral analysis of signals from Mondolfo (top) and Split (bottom) stations
Slika 6. Spektralna analiza signala s postaja Mondolfo (gore) i Split (dolje)

4. NAVTEX SIGNAL MODELING AND DISCUSSION / *Modeliranje NAVTEX signala i rasprava*

In order to further investigate the problem of signal reception during daytime broadcasts of Split and Piombino stations, it was necessary to model and simulate the groundwave propagation losses. The previously mentioned ITU recommendation was used for this purpose. As it states, this recommendation provides information on the field strength and its dependence on ground characteristics due to groundwave propagation at frequencies below 30 MHz, and for the prediction of propagation losses the integral software implementation from its Annex 1 should be used. Also, these prediction methods can be used to determine the field strength over mixed paths as indicated in its Annex 2 [11]. It has already been mentioned previously that the integral software implementation in MATLAB, but without mixed paths (Annex 2), can be downloaded from the ITU website [14]. The specified MATLAB script gives as a calculation result: A_{btl}, basic transmission loss (dB); E, electric field strength (dBμV/m); P_r, received EM field power (dBm) and the calculation method used (flat-earth curve or residue series). In order to determine the output parameters, it is necessary to enter:

- h_t, height of the transmitter (m);
- h_r, height of the receiver (m);
- f, frequency (MHz);
- P_t, transmit power (W);
- N_s, surface refractivity (N-Units);
- d, distance (km);
- ε_r, relative permittivity on the surface of the Earth;
- σ, conductivity on the surface of the Earth (S/m);
- polarization type (vertical or horizontal).

Therefore, in order to determine the propagation losses of NAVTEX signals, it is necessary to enter all of the above parameters, if available. Thus, the available input parameters for the Split station are as follows. The minimum transmitter height is 1 m, because this is the height of the antenna system above the ground, while the maximum transmitter height is 125 m, because this is the height above mean sea level. Likewise, the minimum receiver height is 2 m, while the maximum is 36, in accordance with the previous. The frequency is 490 kHz, while the available values of 200 and 1000 W were taken for the minimum and maximum power. For the surface refractivity in N-Units, the limit values of the software package itself, i.e. the ITU recommendation, were taken. The great circle distance between the Split station and NAVTEX receiver is 286.6 km (154.8 NM). The values of relative permittivity and conductivity on the surface of the Earth were taken in accordance with the ITU manual and recommendation [10], [11]. It was assumed that the propagation path from the Split station to the receiver is mostly over the very dry ground with the conductivity value of 0.0001 S/m, and the relative permittivity value of 3. Vertical polarization was used for calculations since the antenna type of the Split station is vertically polarized folded monopole. In addition, the MATLAB script was modified in terms of gain values of the transmitting and receiving antennas. According to the available data of the Split station, the gain of the transmitting antenna is -3.34 dBd, which is -1.19 dBi, while the data on the gain of the receiving antenna is not known, so 0 dBi was taken. The output parameters, i.e. calculation results, are shown in Table 3.

Table 3 Output parameters for Split station calculated according to ITU recommendation (Annex 1)

Tablica 3. Izlazni parametri za postaju Split izračunati prema preporuci ITU-a (Prilog 1)

Parameter	A_{btl} (dB)	E (dBμV/m)	P_r (dBm)	Method
h_t = 1 m h_r = 2 m f = 0.490 MHz P_t = 200 W N_s = 250 d = 286.6 km ε_r = 3 σ = 0.0001 S/m	137.0966	-14.2564	-85.2603	Residue series
h_t = 125 m h_r = 36 m f = 0.490 MHz P_t = 200 W N_s = 250 d = 286.6 km ε_r = 3 σ = 0.0001 S/m	137.7639	-14.9237	-85.9276	Residue series
h_t = 125 m h_r = 36 m f = 0.490 MHz P_t = 200 W N_s = 400 d = 286.6 km ε_r = 3 σ = 0.0001 S/m	135.6745	-12.8343	-83.8382	Residue series
h_t = 125 m h_r = 36 m f = 0.490 MHz P_t = 1000 W N_s = 400 d = 286.6 km ε_r = 3 σ = 0.0001 S/m	135.6745	-5.8446	-76.8485	Residue series

According to the obtained results from Table 3, it is evident that by changing individual parameters between the maximum and minimum values, the attenuation, or transmission loss, changed by only about 2 dB. It is also evident that the antenna heights have a negligible effect on propagation losses, while the surface refractivity value has a slightly greater effect.

As for the Italian stations, parameters on antenna heights and types are not available, so the minimum antenna height of the Split station was also assumed for these calculations. Furthermore, since the propagation path from the Mondolfo station to the receiver is mostly over seawater, parameters describing its electrical characteristics were taken into the calculation. Thus, the conductivity and permittivity of seawater of average salinity are 5 S/m and 80, respectively. On the other hand, since the propagation path from the Piombino station to the receiver is both over land and over sea, "worse" parameters, i.e. for very dry ground, were taken into the calculation. The results of these calculations are given in Table 4 (Mondolfo) and Table 5 (Piombino).

From the results shown in Tables 4 and 5 it is evident that signal losses, in addition to the type of ground and the atmosphere, also depend on distance. As the Mondolfo station is the closest to the receiver and the propagation path of the NAVTEX signal is almost entirely over seawater, which has very good electrical characteristics, it is evident why the most messages were received from this station. On the other hand, as the Piombino station is the most distant, it is to be expected that the losses are the highest and the smallest number of messages were also received from this station.

Table 4 Output parameters for Mondolfo station calculated according to ITU recommendation (Annex 1)

Tablica 4. Izlazni parametri za postaju Mondolfo izračunati prema preporuci ITU-a (Prilog 1)

Parameter	A_{btl} (dB)	E (dBμV/m)	P_r (dBm)	Method
h_t = 1 m h_r = 2 m f = 0.490 MHz P_t = 200 W N_s = 250 d = 204.4 km ε_r = 80 σ = 5 S/m	74.7305	48.1097	-22.8942	Residue series
h_t = 1 m h_r = 2 m f = 0.490 MHz P_t = 200 W N_s = 400 d = 204.4 km ε_r = 80 σ = 5 S/m	74.0496	48.7906	-22.2133	Residue series
h_t = 1 m h_r = 2 m f = 0.490 MHz P_t = 1000 W N_s = 400 d = 204.4 km ε_r = 80 σ = 5 S/m	74.0496	55.7803	-15.2236	Residue series

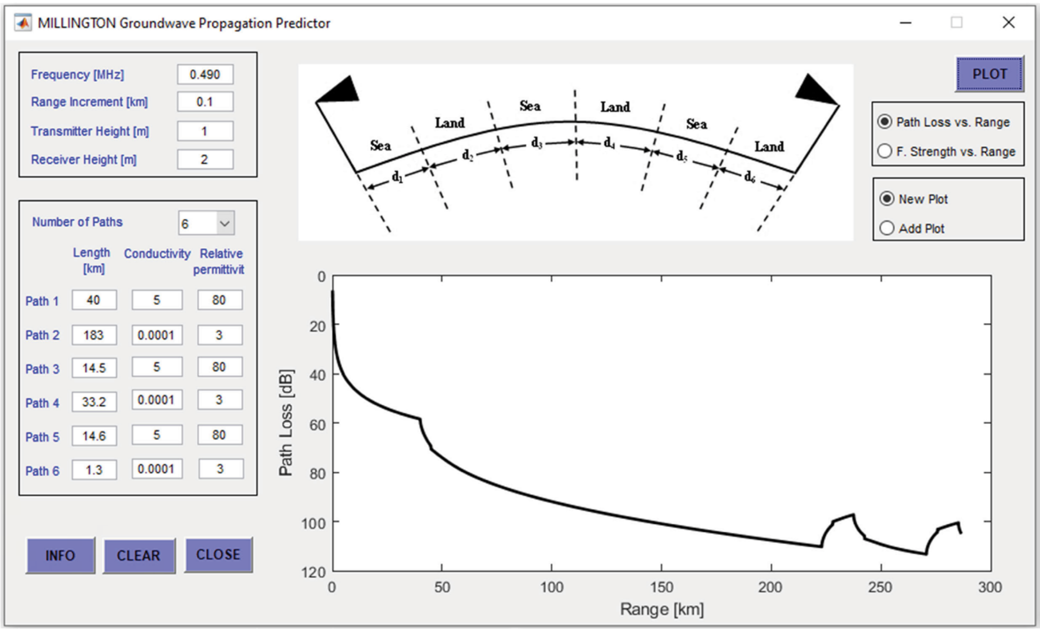
Table 5 Output parameters for Piombino station calculated according to ITU recommendation (Annex 1)

Tablica 5. Izlazni parametri za postaju Piombino izračunati prema preporuci ITU-a (Prilog 1)

Parameter	A_{btl} (dB)	E (dBμV/m)	P_r (dBm)	Method
h_t = 1 m h_r = 2 m f = 0.490 MHz P_t = 200 W N_s = 250 d = 410.7 km ε_r = 3 σ = 0.0001 S/m	148.4407	-25.6005	-96.6044	Residue series
h_t = 1 m h_r = 2 m f = 0.490 MHz P_t = 200 W N_s = 400 d = 410.7 km ε_r = 3 σ = 0.0001 S/m	144.8336	-21.9934	-92.9973	Residue series
h_t = 1 m h_r = 2 m f = 0.490 MHz P_t = 1000 W N_s = 400 d = 410.7 km ε_r = 3 σ = 0.0001 S/m	144.8336	-15.0037	-86.0076	Residue series

However, in order to model the propagation losses more precisely, it was necessary to use the calculation method from Annex 2 of the ITU Recommendation. As already mentioned, for mixed paths there is an available MATLAB tool [15]. The tool called Groundwave Propagation Virtual Tool (GPVT) allows the user to enter the following parameters:

- frequency (MHz);
- range increment (km) for the plot of the path loss;


MILLINGTON Groundwave Propagation Predictor

Frequency [MHz] 0.490
Range Increment [km] 0.1
Transmitter Height [m] 1
Receiver Height [m] 2

Number of Paths 6

	Length [km]	Conductivity	Relative permittivit
Path 1	40	5	80
Path 2	183	0.0001	3
Path 3	14.5	5	80
Path 4	33.2	0.0001	3
Path 5	14.6	5	80
Path 6	1.3	0.0001	3

● Path Loss vs. Range
○ F. Strength vs. Range

● New Plot
○ Add Plot

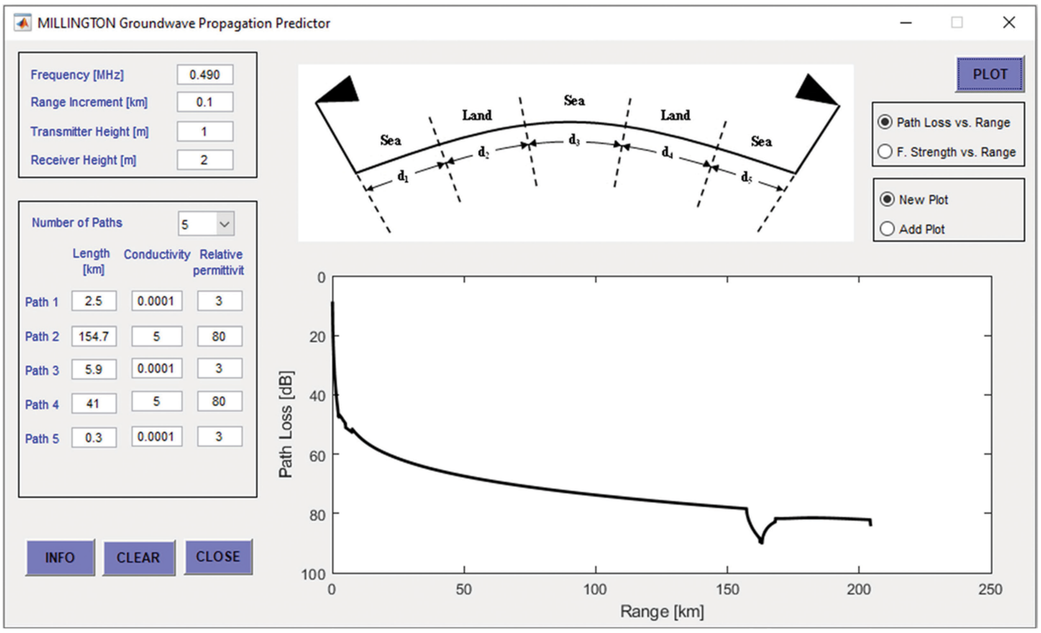
Figure 7 Output results for Split station calculated according to ITU recommendation (Annex 2)
Slika 7. Rezultati izračuna za postaju Split prema preporuci ITU-a (Prilog 2)

- transmitter and receiver heights (m);
- number of paths (1-6);
- length (km), conductivity (S/m) and relative permittivity of each path.

After entering the input parameters, the tool automatically applies Millington's recursive formulas for mixed paths and provides a visual display of the results, i.e. loss and/or field strength. Thus, the propagation path between the Split station and the receiver was divided into 6 paths (land-sea) and the results of the GPVT tool calculations are shown in Figure 7.

Figure 7 shows the effects of recovery when the signal crosses the land-sea boundary. Also, with this calculation method, the total losses at the receiver are 105.06 dB, which is around 30 dB less than with the previous calculation. This also means that the received power is higher by the same amount, which in turn means that the NAVTEX receiver should successfully detect this signal and ultimately demodulate it and decode the messages. Furthermore, the propagation path between the Mondolfo station and the receiver was divided into 5 mixed paths and the results of the GPVT tool calculations are shown in Figure 8. With this calculation method, the total losses at the receiver are 84.29 dB, which is around 10 dB more than in the previous calculation. However, the received power would still be high enough for successful detection and locking to the phasing signal. Finally, the propagation path between the Piombino station and the receiver was also divided into 5 mixed paths and the results of the GPVT tool calculations are shown in Figure 9. With this calculation method, the total losses at the receiver are 125.51 dB, which is around 20 dB less than in the previous calculation. Therefore, as in the case of the Split station, this would mean that the NAVTEX receiver should also successfully detect the received signal.

There are other MATLAB tools that use numerical methods for predicting groundwave propagation losses. As already


MILLINGTON Groundwave Propagation Predictor

Frequency [MHz] 0.490
Range Increment [km] 0.1
Transmitter Height [m] 1
Receiver Height [m] 2

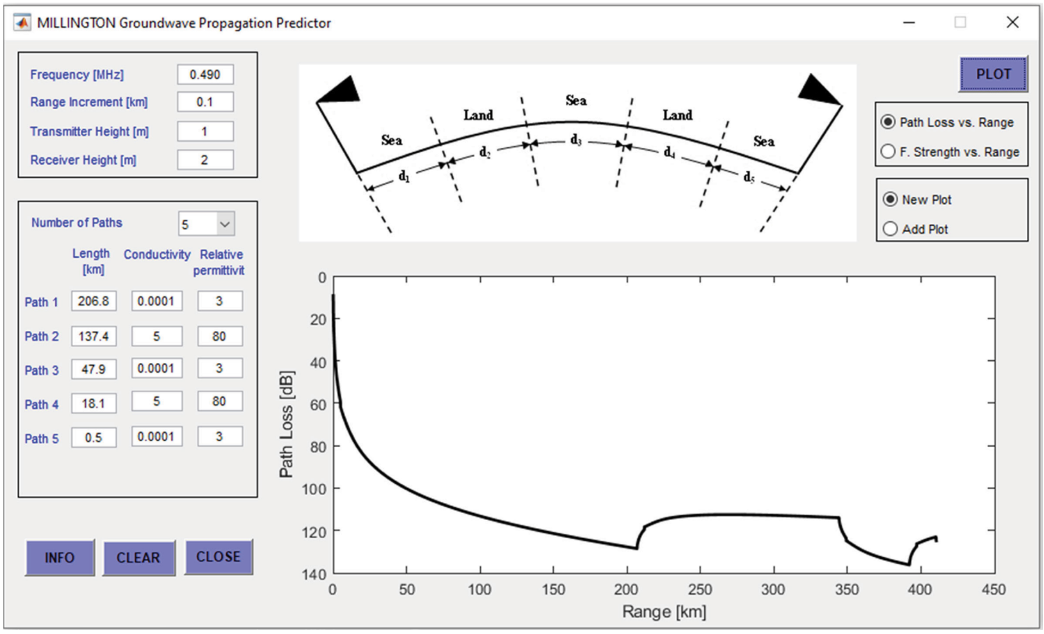
Number of Paths 5

	Length [km]	Conductivity	Relative permittivit
Path 1	2.5	0.0001	3
Path 2	154.7	5	80
Path 3	5.9	0.0001	3
Path 4	41	5	80
Path 5	0.3	0.0001	3

● Path Loss vs. Range
○ F. Strength vs. Range

● New Plot
○ Add Plot

Figure 8 Output results for Mondolfo station calculated according to ITU recommendation (Annex 2)
Slika 8. Rezultati izračuna za postaju Mondolfo prema preporuci ITU-a (Prilog 2)



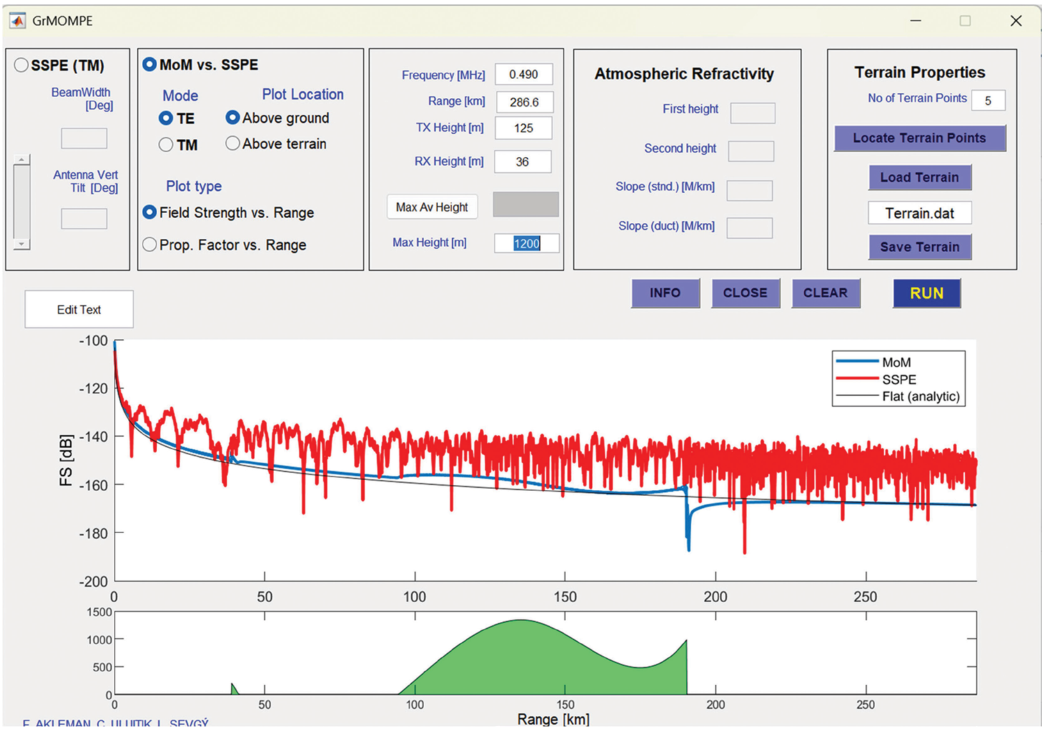
Frequency [MHz] 0.490
Range Increment [km] 0.1
Transmitter Height [m] 1
Receiver Height [m] 2
Number of Paths 5

	Length [km]	Conductivity	Relative permittivit
Path 1	206.8	0.0001	3
Path 2	137.4	5	80
Path 3	47.9	0.0001	3
Path 4	18.1	5	80
Path 5	0.5	0.0001	3

● Path Loss vs. Range
○ F. Strength vs. Range
● New Plot
○ Add Plot

Figure 9 Output results for Piombino station calculated according to ITU recommendation (Annex 2)
Slika 9. Rezultati izračuna za postaju Piombino prema preporuci ITU-a (Prilog 2)

mentioned, a MATLAB simulator was developed that combines the Method of Moments (MoM) and Split-Step Parabolic Equation (SSPE) methods for predicting field strengths during ground wave propagation [17]. This simulator allows for direct comparison of results obtained by two different numerical approaches, depending on propagation parameters and terrain complexity, and comparison with analytical tools (ITU recommendation). The user interface in MATLAB intuitively offers parameter input. Also, the user can draw arbitrary terrain profiles by selecting the number of terrain points. However, for all three observed stations, after entering all necessary parameters and with an approximation of the terrain configuration (the lowest and highest terrain points along the propagation paths), the obtained results showed better performance compared to previous calculations, i.e. lower signal losses. It is also previously mentioned that a MATLAB tool which uses Finite Element Method and Parabolic Equation (FEMPE) to accurately calculate signal losses along uneven terrain with different electrical characteristics was presented in [18]. The user interface of the tool allows visualization and editing of terrain profiles by entering frequency, range increments, number of terrain points, length and type of each path, electrical properties of the ground and refractivity profiles. The user can choose between analytical (ITU recommendation) and numerical (FEMPE) methods and compare them. However, as with the previous tool, for all three observed stations, after entering all the necessary parameters



○ SSPE (TM)
● MoM vs. SSPE
Mode
● TE
○ TM
Plot Location
● Above ground
○ Above terrain
Plot type
● Field Strength vs. Range
○ Prop. Factor vs. Range
Frequency [MHz] 0.490
Range [km] 286.6
TX Height [m] 125
RX Height [m] 36
Max Height [m] 1200
No of Terrain Points 5
Terrain.dat

Figure 10 Output results for Split station calculated using MoM and SSPE methods
Slika 10. Rezultati proračuna za postaju Split dobiveni korištenjem MoM i SSPE metodama

and with an approximation of the terrain configuration, the obtained results showed better performance compared to previous calculations, i.e. lower signal losses. The result of the calculation of the MATLAB simulator using the MoM and SSPE methods for the Split station can be seen in Figure 10. The other graphs generated using the previous two MATLAB tools show the same pattern and therefore were not presented.

Therefore, from the previous analysis and comparison between the actual measured values of received signal strength during daytime broadcasts of in range NAVTEX stations and the values obtained by analytical and numerical models, it is evident that there are significant deviations and it can be concluded that in this specific case the mentioned models cannot be used to predict the propagation of the NAVTEX signal. It can also be concluded that, although propagation models provide valuable insights into the behavior of groundwaves, significant deviations between predicted and measured results indicate inadequately modeled environmental factors, potential problems with the performance of the transmitting stations or specific characteristics of the local receiving system. The fact that the signals from the Split and Piombino stations are not stable and cannot be detected indicates potential fading, multipath or intermittent interference. Such phenomena can seriously degrade the performance of digital communication, even if the peak signal strength occasionally reaches the detection threshold. For digital signals such as NAVTEX, continuous and stable reception is essential for error-free message reception and decoding.

5. CONCLUSIONS / *Zaključci*

This research successfully analyzed the reception of NAVTEX signals and measured the signal strength during daytime broadcasts, achieving its key objective. A detailed analysis of the collected data confirmed a significant anomaly: the consistent failure of message reception from the Split and Piombino stations during daytime hours, despite their proximity and the fact that the receiver is within their range. At the same time, the signal reception from the nearest Mondolfo station was reliable and stable. The second objective of the research, modeling and simulation of groundwave propagation using established tools, clearly showed that these models predict signal strengths that should be detectable for the Split and Piombino stations, which is in direct contradiction to experimental observations. Even for Mondolfo station, where reception was successful, a significant quantitative difference was observed between the measured and modeled values, indicating the limitations of the model in achieving full quantitative accuracy.

The key finding of this research is that standard propagation models, despite their widespread application, fail to accurately predict the behavior of NAVTEX signals in the complex coastal environments of the northern Adriatic. This discrepancy indicates an inadequate capture of critical environmental factors, such as the complex micro-topography of coastal areas, dynamic atmospheric effects such as fading and multipath, or potential performance issues with the transmitters themselves. Consequently, relying on these models for planning radio coverage in such areas may lead to inaccurate predictions and compromise maritime safety by creating unexpected "blind spots".

These findings open important directions for future research. More detailed terrain mapping and the integration of more precise atmospheric profiles, obtained for example by radiosondes or satellite data, into propagation models are recommended to improve their predictive ability. Extending the measurement period to monitor long-term seasonal and daily variations in propagation is essential to identify recurring patterns of fading and other dynamic effects. Furthermore, a direct investigation of the transmitter performance at the Split and Piombino stations, including measurements of output power and antenna characteristics, could reveal potential causes of the weak signal. The development and application of more advanced dynamic models capable of simulating effects such as fading and multipath are also imperative for more reliable prediction of digital communication systems. Finally, a detailed analysis of the local electromagnetic noise at the receiving location, especially during daylight hours, could identify potential sources of interference that degrade the signal.

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