LRPT WEATHER SATELLITE IMAGE ACQUISITION USING A SDR-BASED RECEPTION SYSTEM

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Abstract: The LRPT (Low Rate Picture Transmission) direct broadcast service provides imagery from polar-orbiting weather satellites directly to end users. As a digital transmission system within VHF band, its main purpose is to replace the analog APT (Automatic Picture Transmission) system, still available on NOAA (National Oceanic and Atmospheric Administration) polar satellite fleet. This paper presents some aspects involving the reception and decoding of high-resolution LRPT images provided by the Russian Meteor-M N2 weather satellite, using a VHF reception system based on software-defined radio (SDR). The experimental tests were undertaken in order monitor and evaluate the performance of LRPT broadcast service during in-orbit commissioning test phase of the satellite. This paper also presents some guidelines and conclusions drawn from these experiments.

Keywords: *LRPT, SDR, weather, Meteor-M N2.*

I. INTRODUCTION

In the VHF band (137 – 138 MHz), remotely sensed meteorological data is transmitted directly from polar-orbiting satellites to end users within signal range of the satellite. Currently, the APT (Automatic Picture Transmission) broadcast analog system on-board NOAA POES satellites (National Oceanic and Atmospheric Administration – Polar Orbiting Environmental Satellites) is the most popular direct readout service used to disseminate low-resolution image data products, in near-real time [1].

However, the increasing demand on scientific data has led to the migration to more complex digital services like LRPT (Low Rate Picture Transmission) [2], with the main purpose of improving the quality, quantity and availability of meteorological data from direct broadcast meteorological satellites.

I.1. LRPT Direct Broadcast Service Description

LRPT is a digital broadcast transmission system designed to provide data and images from polar-orbiting weather satellites directly to end users. This system represented a joint effort between EUMETSAT (European Organization for the Exploitation of Meteorological Satellites) and NOAA in developing a new dissemination standard within VHF band, for current and future weather satellite programs. LRPT is very similar with the present-day HRPT (High Rate Picture Transmission) transmission system and is characterized by the implementation of CCSDS (Consultative Committee for Space Data Systems) [3] specifications.

Basically, the LRPT system is an update and replacement of the APT (Automatic Picture Transmission) analog system which is still used to provide imagery derived from the AVHRR/3 (Advanced Very High Resolution Radiometer) instrument on-board NOAA polar-orbiting satellites (NOAA -15,-18,-19) [4].

The LRPT system provides three compressed image channels derived from the AVHRR/3 instrument (10-bit, 1 km/pixel), in addition to data from other sensors. In contrast, the APT system provides only two image channels, which are at reduced resolution and accuracy (4 km/pixel, 8-bit) [5]. By comparison with the APT images, LRPT images contain twelve times more resolution and are four times more accurate.

In LRPT, different scientific data is acquired as CCSDS source packets. The packets are then formatted and multiplexed, resulting in a packetized datastream of 72 kbps (including Reed-Solomon error correction). Each sensor is considered an application and is provided a fraction of the transmission bandwidth, in the form of a virtual channel. For example, the three image channels provided by AVHRR/3 instrument requires 40 kbps in terms of bandwidth. In order to fit the allocated virtual channel, the AVHRR/3 raw image data is compressed using a JPEG extended compression algorithm, adapted to a fix compression ratio. [6]

At LRPT physical layer, the datastream is convolution encoded, interleaved and padded with unique synchronization words, resulting in a binary stream of approximately 160 kbps. According with LRPT specifications [7], data is transmitted as a QPSK (Quadrature Phase-Shift Keying) signal on a 137 MHz carrier, at data rates up to 80 KSymb/s, with an EIRP (Effective Isotropic Radiated Power) level that varies between 3.2 dBW and 8 dBW (2 - 6.3W). The signal is RHCP polarized, while the required RF bandwidth is 150 KHz.

The first LRPT operational service was available on MetOp-A satellite [8]. However, due to on-board equipment

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anomalies, it has been decided to completely abandon it, since it has been proven unfeasible to rectify these problems for the future MetOp-B,-C satellites [9]. After many years, LRPT direct readout service was resumed, with the launch of Meteor-M N2 satellite.

I.2. Meteor-M N2 Weather Satellite Overview

On July 8, 2014, Russia launched into orbit its latest version of remote-sensing and weather-forecasting satellite, known as Meteor-M N2. It is the second satellite deployed within Meteor-M series of polar-orbiting satellites to be used in support of different Russian hydro-meteorological and environment monitoring agencies [10]. The overall objective of Meteor-M N2 spacecraft is to provide for the next five years, global observations of the Earth's atmosphere and its surface. Its main mission is to collect scientific data related to global climate change monitoring, weather forecasting at regional and global scale, sea water monitoring and forecasting, or space weather analysis and prediction.

The Meteor-M N2 satellite was launched on a 98.8° inclination, sun-synchronous near-circular polar orbit using a Soyuz-2.1b/Fregat launcher. It is orbiting the Earth at an average altitude of 832 km, having an orbital period of approximately 101 minutes [11]. The descending equatorial crossing time is at approximately 09:30 (Moscow local time).

There are several scientific instruments on-board the spacecraft. The MSU-MR instrument is a low-resolution multispectral scanner designed mainly for meteorological purposes: cloud cover mapping information and sea/land surface temperatures. This optomechanical instrument provides imagery in six different bands in the VIS/IR spectral regions and has a spatial resolution of approximately 1 km at Nadir [12]. Basically, this instrument is very similar in function and performance with the AVHRR/3 instrument on-board POES missions of NOAA. Table 1 illustrates the spectral bands used by the MSU-MR imaging radiometer.

No.	Band	Nominal spectral band
1	Visible	0.5 - 0.7 ± 0.2 µm
2	Visible Near Infrared	0.7 - 1.1 ± 0.2 µm
3	Short Wave Infrared	1.6 - 1.8 ± 0.50 µm
4	Mid Wave Infrared	3.5 - 4.1 ± 0.50 µm
5	Thermal Infrared	10.5 - 11.5 ± 0.50 µm
6	Thermal Infrared	11.5 - 12.5 ± 0.50 µm

Table 1. MSU-MR radiometer spectral bands

The scientific data provided by the MSU-MR instrument is disseminated using LRPT (VHF band) and HRPT (L-band) communication standards according with WMO (World Meteorological Organization) recommendations in order to permit information exchange at international level.

The LRPT service on-board Meteor-M N2 spacecraft provides mainly compressed resolution imagery from the active channels of the MSU-MR instrument. Details regarding the MSU-MR data handling are presented in [13]. The information is transmitted in direct broadcast mode according with a pre-programmed time schedule. Currently, the LRPT broadcast service is operational on 137.100 MHz, transmitting at data rates of 72 kbps (QPSK modulation) in international LRPT format. In operational mode, the following MSU-MR channels will be available for dissemination: channels 1, 2 (VIS) and 5 (IR). Unfortunately, there is no channel switching planned at the terminator line crossing (day/night). As a consequence, during night time passes of the spacecraft, there will be no useful data disseminated by channels 1 and 2.

II. LRPT RECEPTION SYSTEM SETUP

LRPT reception systems are more complex than traditional APTs [14]. A typical reception system must be equipped with hardware capable of performing demodulation, bit and frame synchronization and processing the stream of packetized data units. Also, computer software is required to decode, sort and decompress the data in the desired format [15]. Fortunately, with the advent of software-defined radio receivers, the complexity is reduced significantly since most of the above-mentioned processes are performed in software.

Similar work related with the monitoring of Meteor-M N2 has been performed mainly by amateur radio community. In fact, comprehensive tutorials regarding LRPT image acquisition under Windows/Linux environments are available online [16]. However, most of the reception designs presented are based on cheap SDR receiver like RTL2832U-based dongle.

The following chapter presents some details regarding the solution used in terms of hardware and software for successful reception of LRPT images from Meteor-M N2.

II.2 Hardware Description

Fig. 1 illustrates a simplified block diagram of the LRPT reception system. This implementation is based mainly on commercial off-the shelf (COTS) hardware.

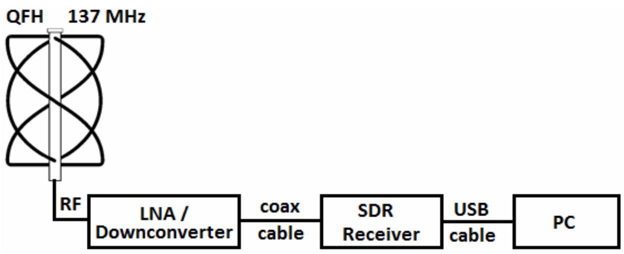

Figure 1. Current LRPT reception system implemented

There are many different omnidirectional antenna designs (Lindenblad, turnstile, crossed Yagi, etc.) used for weather satellite reception. Unfortunately, these designs only partially comply with the RHCP requirements and are more or less satisfactory in terms of performance.

An optimal solution to this problem is the QFH (Quadrifilar Helix) antenna design, which provides better performance in terms of gain, circular polarization and radiation patterns compared with other designs. Currently, there are numerous antenna versions starting from the QFH classical design. The solution implemented is based on W3KH antenna design [17]. It is a "½ turn, ½ λ" type antenna with R=0.44 (where R represents the ratio between the diameter and the axial length of the antenna).

The physical dimensions of the antenna are provided by simulations made using a QFH online calculator [18], while the assembly procedure is based on tutorials/manuals made available [19]. Circular polarization (RHCP) is achieved using a self-phasing big/small loop configuration. An infinite balun matching-scheme [20] is used to produce a characteristic impedance of approximately 50Ω.

The fully assembled antenna is presented in Fig. 2a. Note that, mast and support arms of the antenna were constructed of PVC tubes, while the loops were made entirely from Tri-Lan 240 coaxial cable in order to provide extra rigidity when shaping the antenna.

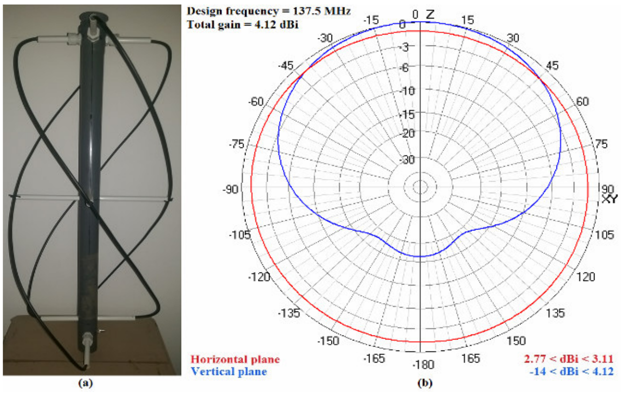

Figure 2. Fully assembled QFH antenna (a); Theoretical radiation diagram using 4NEC2 software (b)

Design simulations were performed using 4NEC2 antenna modeler and optimizer software [21]. For the designed frequency (137.5 MHz), the theoretical radiation pattern is almost hemispherical. In the azimuth plane, the radiation patterns are symmetrical with negligible gain variations. In the elevation plane, the radiation patterns are almost constant up to very low elevation angles, resulting in a -3dB beam width higher than 130° (and -6 dB beam width of 170°) – see Fig. 2b. The theoretical peak gain (on vertical direction) is approximately 4 dBi.

The QFH antenna was installed on top of a 6 m mast, in order to have clear visibility towards the horizon. A down-converter was installed near the antenna in order to translate the received VHF signal into HF frequency domain. Also, the device acts as a low-noise amplifier in order to improve the noise figure of the reception system, consequently to improve the SNR (signal-to-noise ratio) of the incoming radio signals. The selected down-converter [22] provides a conversion gain of 20 dB with a noise figure of 0.5 dB.
In order to avoid additional signal losses, 50Ω low-loss LMR-400 coaxial cable was used.

SDR-IQ is a high-performance software defined radio receiver that operates in the HF band (500 Hz – 30 MHz). It is equipped with a 14-bit ADC running at a sample rate of 65 MSPS [23]. Digital data is processed into I and Q format using a direct digital converter (DDC) and sent through USB interface to PC for further processing. This device provides a maximum display bandwidth of 190 KHz for real-time monitoring of the RF spectrum. All the software processing is performed on a typical PC.

II.2. Software Description

Different proprietary or open-source software packages are required for reception and decoding of LRPT image data.

Based on accurate time reference, geographical coordinates and up-to-date TLEs (Two-Line Element set), Orbitron software provides information regarding satellite predictions at any given moment. SpectraVue software performs real-time FFT spectral analysis on the received RF signals, displays and decodes data in various formats. It will be mainly used for recording and processing I/Q data files from the SDR-IQ receiver. Dedicated software was used for offline processing and decoding of LRPT images. The software made available was designed only for experimental and educational purposes [24]. Some of the software's functionality will be presented in the following chapter.

III. EXPERIMENTAL RESULTS

Different experimental tests were undertaken in order monitor the Meteor-M N2's LRPT broadcast service, during the in-orbit commissioning test phase. Another reason was to evaluate the performance of the LRPT reception system used. Between September – December 2014, more than 90 descending passes (morning passes) of the Meteor-M N2 satellite were successfully monitored within the reception range of the station. For each satellite pass monitored, LRPT images were decoded according with the following procedure.

III.1. LRPT Image Decoding Procedure

The procedure of decoding of LRPT imagery under Windows OS environment involves several steps, which must be performed in the following order.

- **Real-time recording of the RF spectrum containing the signal from Meteor-M N2 spacecraft, during the entire pass.**

A baseband I/Q WAV file must be recorded by the SDR-IQ receiver, at a sample rate of at least 150 KSPS, in order to fit the envelope of the received signal. The downlink frequency of Meteor-M N2 satellite must be the center frequency of SpectraVue recording software. Fig. 3 shows for illustration purposes, the spectrogram of the received carrier signal from Meteor-M N2 spacecraft, in waterfall mode.

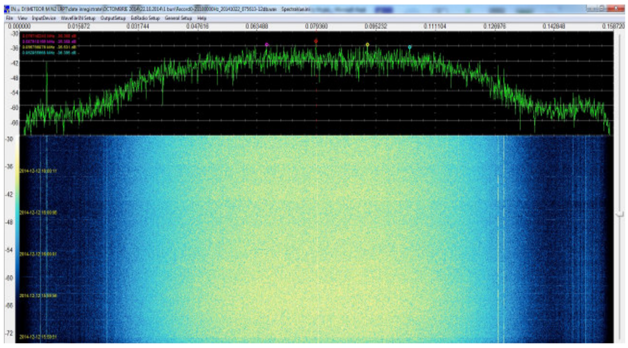

Figure 3. Sample of RF spectrum recorded using SDR-IQ receiver

- **Offline processing of the recorded I/Q WAV file using dedicated software for soft-symbol extraction purposes.**

The software performs QPSK demodulation and produces an output RAW file containing soft-symbol information used to decode LRPT images. Note that, being educational software, there is no proper documentation regarding its operation and functionality. Therefore, most of the parameters were left to default values.

Quality improvement on the QPSK constellation is possible by resampling the recorded I/Q WAV file to lower values (e.g. 130 KSPS) and even by digitally amplifying it using open-source audio editing software like Audacity. Fig. 4 illustrates the constellation diagram obtained during QPSK demodulation.

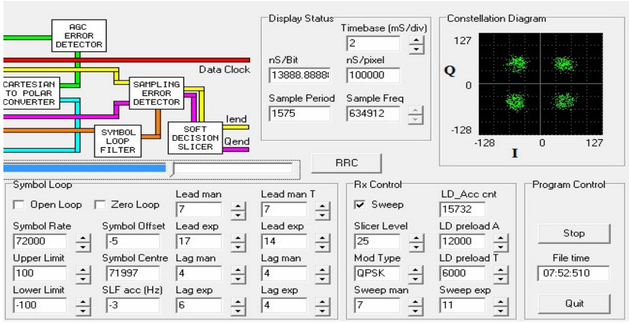

Figure 4. A well-defined four point constellation implies the successful QPSK demodulation of the received signal

- **Analyzing the RAW file and extracting imagery using dedicated LRPT decoding software.**

By processing the RAW file, the LRPT decoding software automatically produces high-resolution images in BMP/JPEG format, for the corresponding active channels of the MSU-MR instrument on-board Meteor-M N2 spacecraft. Fig. 5 illustrates samples of decoded image data.

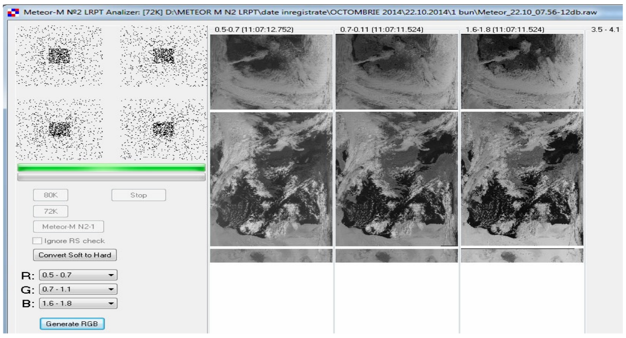

Figure 5. Unenhanced grayscale decoded images for the corresponding MSU-MR active channels.

A multispectral analysis feature of the software generates false-colored images by combining the decoded grayscale images. Also, additional log files (e.g. calibration data) may be generated on demand.

III.2. LRPT Image Samples

Raw data images were received from Meteor-M N2 spacecraft on 22nd of October 2014, between 07:54 and 08:07 UTC, during an 80° elevation southbound pass. The satellite was travelling West relative to the reception point (Cluj-Napoca). Fig. 6 shows computed data information regarding the characterization of satellite's pass.

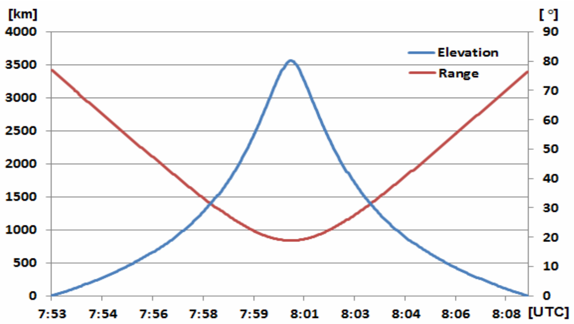

Figure 6. Range versus elevation for the corresponding Meteor-M N2 pass (10/22/2014, Orbit #1496)

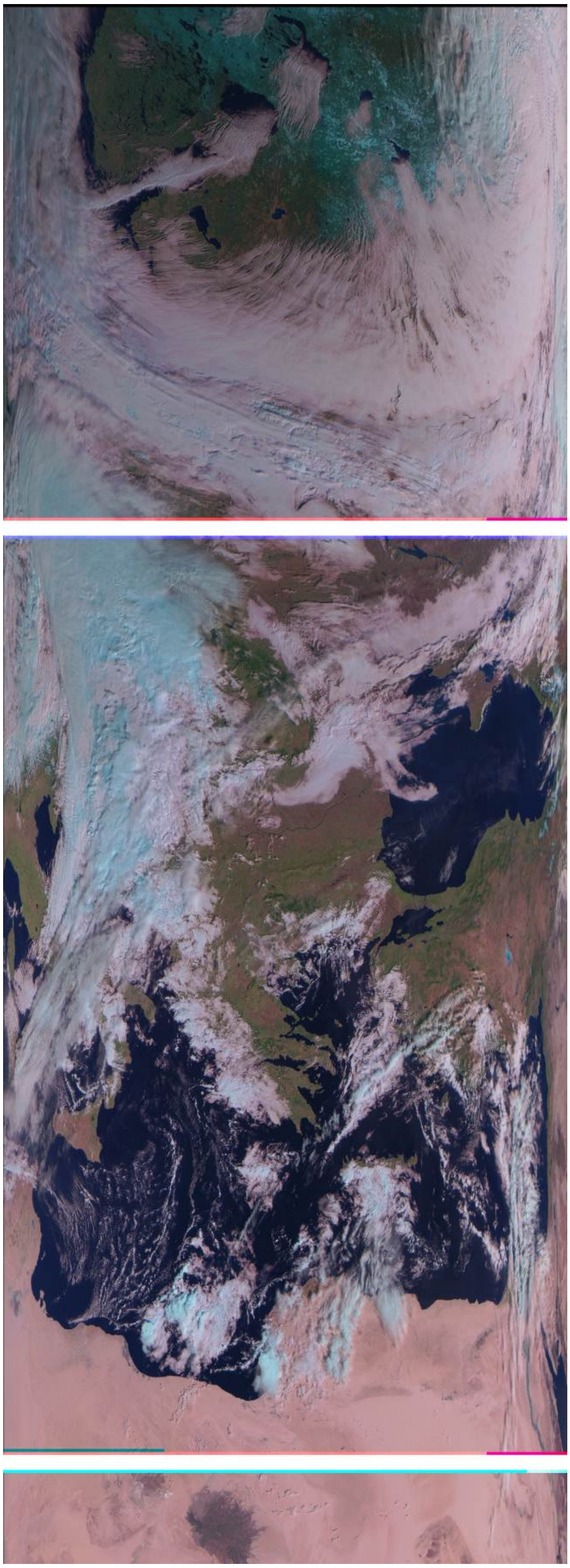

Figure 7. Multispectral analysis (MSU-MR channels 1-3) from Meteor-M N2 (10/22/2014, Orbit #1496)

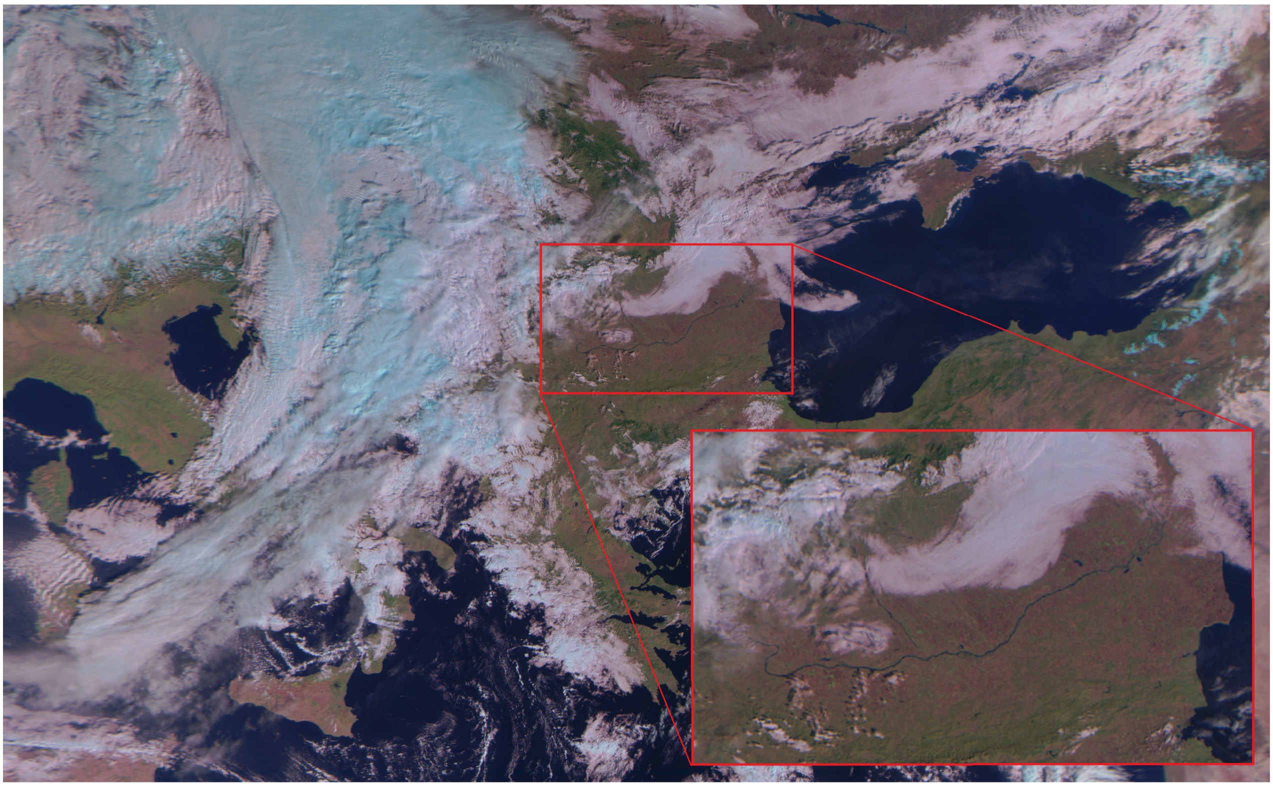

Figure 8. Section of a "normalized" image received from Meteor-M N2 (10/22/2014). When zoomed in, the image provides a high-degree of details (e.g. the course of Danube River).

Fig. 7 illustrates a vivid false-colored image as a result of multispectral analysis. The image is 1568 pixels wide, having a corresponding swath width of approximately 2800 km. Note that, the image reveals two white stripes, which are caused by a malfunction on the LRPT adapter unit (raw HRPT to LRPT JPEG compression system) on-board the satellite [24]. These stripes last for 6 seconds and occur periodically every 6 and half minutes. Apparently, this issue has not been solved yet. The geometric distortions observed in Fig. 7 at the left and right edges of the image are caused by the curvature of the Earth. A "normalized" version of the image may be produced using dedicated image processing software [24].

As observed in Fig. 8, the image provides a high-degree of details especially near the center of the image where the spatial resolution is almost the same (1km/pixel at satellite's Nadir). At the edges of the image, the resolution is less. This is because the information contained within the pixels close to the edges of the original image is sporadic. During rectification, these pixels are stretched within a smoothing image process.

III.3. Comments on the Experimental Results

The acquisition of LRPT images was based mainly on trial & error reception experiments, since there was not enough scientific information made available. For instance, limited information has been identified regarding the VHF communication subsystem on-board the Meteor-M N2 satellite (antenna's radiation pattern, EIRP, etc.). As a consequence, the final design of the reception system was based on MetOp/LRPT link budget estimations [25] and previous experience in receiving APT images from NOAA weather satellites.

During the monitoring period, there were cases when the decoded information from Meteor-M N2 satellite did not contained any image data. This issue was caused by total blockage of the HRPT/LRPT adapter unit. Therefore, the satellite was broadcasting fill (zero) data packets, until a reset command was performed by the ground control team.

In general, the constructed QFH antenna produces good results. High quality images are obtained especially during high-elevation passes of the satellite. For low-elevation passes, the interferences and background noise affects the strength of the received signal, resulting in artifacts on the decoded image.

For this current configuration, proper QPSK demodulation is achieved for elevations higher than 15°. It requires between 5 and 10 dB of SNR for the Costas loop (carrier recovery and tracking) to synchronize with the signal. Also, reducing the carrier tracking loop bandwidth (± 4 KHz instead of ± 10 KHz) will provide a faster lock on the satellite's carrier. Under normal conditions, assuming proper frequency calibration of the SDR-IQ receiver, the Doppler Shift (approximately 3 KHz at 137 MHz) does not exceed that range.

A common problem encountered during monitoring, represented the presence of artifacts in the decoded images (other than the white stripes). While most of them may be explained by local and RF propagation conditions, some may be related with software processing or hardware issues.

In certain situations, the resulted artifacts were correlated with sudden variations observed in the received signal strength. These fluctuations may be explained by the irregularities in the antenna's radiation pattern. This is most probably related to construction issues, since the loops are built from coaxial cable and the antenna doesn't have its ideal helical shape.

Also, slow performing PCs (with overloaded CPU or USB controllers) may lead to phase jitter, which will result in the appearance of artifacts. This is caused mainly by missing I/Q samples, which were dropped and not recorded by the SDR software.

The entire reception and decoding process under Windows OS environment is time consuming. It may take up to half an hour depending on software version and PC configuration (e.g. Core 2 Duo 2.4 GHz / 2 GB RAM / Windows 7-32bit – the configuration used). Also, extra storage on HDD may be temporarily required for the resulted data files (a 12 minutes satellite pass requires approximately 600 Mb of free space).

IV. CONCLUSIONS

The acquisition of weather satellite imagery in the VHF band became very popular over the years, within the user community, mainly because it involved using low-cost reception systems. The reception of near real-time satellite imagery looked to be on the way out, as APT analog system entered its final phase with the launch of NOAA-19 spacecraft.

In the near future, it will to be replaced by its digital equivalent known as LRPT. Apparently, this implies that reception systems will become more complex than traditional APTs. Fortunately, with the advent of software defined radio (SDR) receivers, the design of LRPT reception systems may be kept at the same level of complexity, since most of the processes will be performed in software. The LRPT service on-board Meteor-M series could prolong the direct reception of weather satellite imagery, long after NOAA satellites cease to function.

This paper presented some guidelines and own conclusions regarding the reception experiments undertaken during in-orbit commissioning test phase of Meteor-M N2 satellite. Currently, the LRPT broadcast service on-board Meteor-M N2 is operational with certain limitations, providing high-resolution satellite imagery to the user community.

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