A WEATHER SATELLITE BASED PLATFORM FOR SIGNAL PROCESSING EDUCATION

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ABSTRACT

In this paper, we present the concept of a weather satellite based platform for signal processing education. The platform consists of a receiver subsystem for public NOAA weather satellites and a signal processing subsystem for different applications like weather image reconstruction, weather image processing, localization of the receiving antenna, and array processing. The goal is to raise the interest of students on signal processing and to offer a project laboratory platform to students who can experiment with different signal processing algorithms to solve a number of practical problems.

***Index Terms*—** signal processing education, weather satellite, receiver, weather image, localization

1. INTRODUCTION

One problem in signal processing education is that signal processing is often hidden to beginners. For example, when using a mobile phone, the user is normally not aware of the existence of all the signal processing algorithms in the mobile phone for the physical layer (synchronization, equalization, data detection, channel codec) and application layer (speech processing like voice codec, echo cancelation, speech recognition, image processing, localization etc). In order to raise the interest of students in signal processing, it is important to offer courses which are both demanding in theory and methods and exciting. Following this basic idea, we have developed a weather satellite based platform for signal processing demonstration and education. A self developed receiver for public weather satellites records satellite signals containing weather images. Based on these signals, we have designed different practical signal processing tasks. We show students or students can learn during a project laboratory course where and how signal processing algorithms can be successively applied to solve real-life problems.

The paper is organized as follows. Section 2 introduces the weather satellites we use. The receiver subsystem is briefly described in section 3. Section 4 explains in detail the signal processing subsystem including various tasks to be solved by students. Finally, we present the concept of how to use this platform in a project laboratory course in section 5.

2. WEATHER SATELLITES

The weather satellites we use are part of the U.S. National Oceanic and Atmospheric Administration (NOAA) Polar Orbiting Environmental Satellites (POES) system [1]. The first of these satellites was launched in 1960. Today several satellites are active. They fly on a low earth orbit (LEO) with an altitude of around 833-870 km above the earth surface. The travel time of one orbit is approximately 102 minutes. One satellite is visible to the ground station for about 15 minutes depending on the actual orbit.

The satellites scan the earth on a line perpendicular to the flight direction. Several channels of measurements in different spectral bands are obtained by the Advanced Very High Resolution Radiometer (AVHRR). By using the Automatic Picture Transmission (APT) system, two of these channels, normally the visible light and the infrared image, are combined according to the APT line format in Fig. 1. They are D/A-converted and sent to the earth by an analog amplitude modulation (AM) followed by a frequency modulation (FM), see Fig. 2.

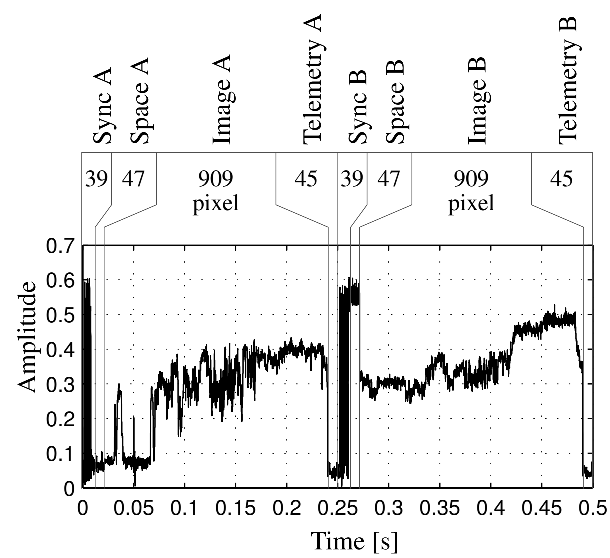

Fig. 1. APT line format

Each APT line is 0.5 second long. Each line contains 909 pixels for one channel where each pixel corresponds to

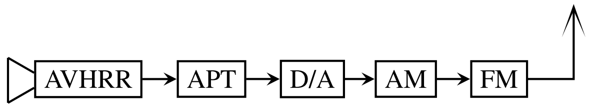

Fig. 2. Satellite transmission system

an earth surface resolution of $4 \times 4\,\text{km}^2$. Both images are in grayscale. They are synchronized with two different rectangular synchronization signals Sync A and Sync B. After the D/A conversion, the analog signal with a bandwidth of roughly 2 kHz is amplitude modulated on a 2.4 kHz audible carrier. The resulting AM-signal is frequency modulated on a carrier in the range of 137-138 MHz. Each satellite uses a different FM carrier. The radio signal bandwidth is about 40 kHz. For a satellite pass of 15 minutes, 1800 APT lines are received. Each 1800×909 image covers an earth surface area of $7200 \times 3636\,\text{km}^2$. Fig. 3 shows a sample image covering Europe and part of northern Africa.

3. THE RECEIVER SUBSYSTEM

We have developed a receiver subsystem for the NOAA weather satellites. All hardware and software have been designed and realized by students in their Diploma or semester theses. The design is quite straightforward as shown in Fig. 4. We use an omnidirectional quadrifilar helicoidal antenna positioned on the roof of our building. After amplification of the weak radio signal with two low noise amplifiers, the signal is converted to an intermediate frequency (IF) of 10.7 MHz for filtering and further amplification. The mixing local oscillator is controlled by a microcontroller. The frequency and gain setting is performed via an USB interface by a PC. The IF signal is then mixed to the zero-IF I/Q baseband as well as demodulated using an analog frequency demodulator for reference. The A/D conversion is performed using a standard multichannel sound card with a sampling frequency of 96 kHz. The resulting baseband signal is stored in the WAV format. Fig. 5 shows the receiver board.

4. THE SIGNAL PROCESSING SUBSYSTEM

Each time when an NOAA satellite flies over the observer, the receiver subsystem records a multichannel WAV file. For a sampling frequency of 96 kHz and a satellite pass of 15 minutes, the WAV file size is roughly 500 MB. The digital signal processing afterwards is off-line. Below we describe several signal processing tasks which process the recorded signals for different purposes. We also present a reference solution for each task. The tasks have been selected according to the criteria: a) they are based on the weather satellite signals, b) they require various signal processing algorithms, c) they are exciting but simple enough for undergraduate students with only

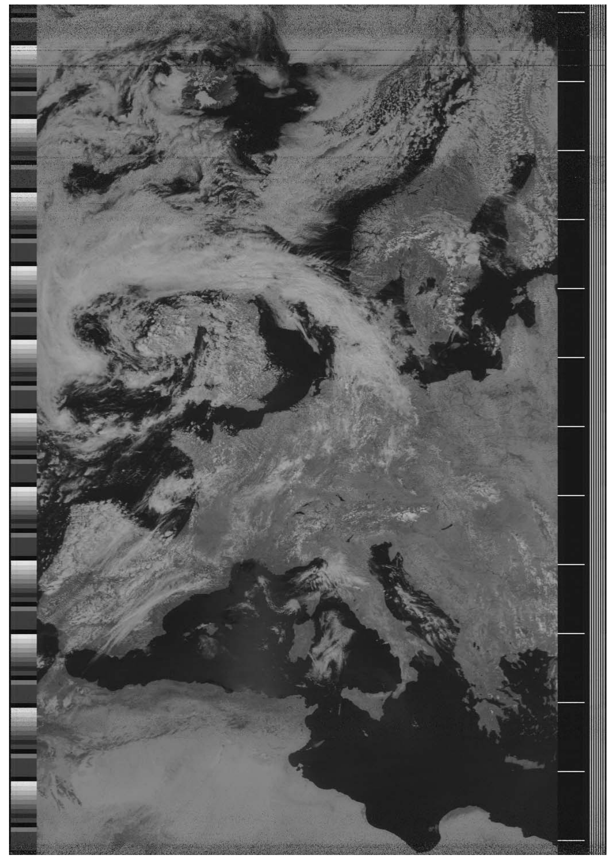

Fig. 3. A weather image recorded on 2007/06/20, 12.27UTC from the satellite “NOAA 18”. It flew from south to north. Therefore, the synchronization signal is at the right boundary of the image. The noisy lines at the top and bottom of the image are due to signal shadowing caused by surrounding buildings.

a basic understanding of digital signal processing.

4.1. Weather image reconstruction

The first natural signal processing task is the weather image reconstruction. Fig. 6 shows its signal processing flow. Normally, the complex baseband IQ signal is used as it contains more information than the FM demodulated signal like signal strength and DC offset. As for all multichannel systems, mismatch in amplitude and phase between the I and Q component can occur. The first step is therefore a calibration. Several algorithms exist for this purpose. The simplest method we use is to compensate the amplitude mismatch only based on energy estimates of the I and Q component. After the calibration, a lowpass filtering with the corner frequency at 25 kHz helps to suppress noise and interferences from neighbor channels. Digital FM demodulation follows then to obtain the AM signal. We obtained a quite good result by using the FM demodulation algorithm from [2] or the pulse pair demodulator

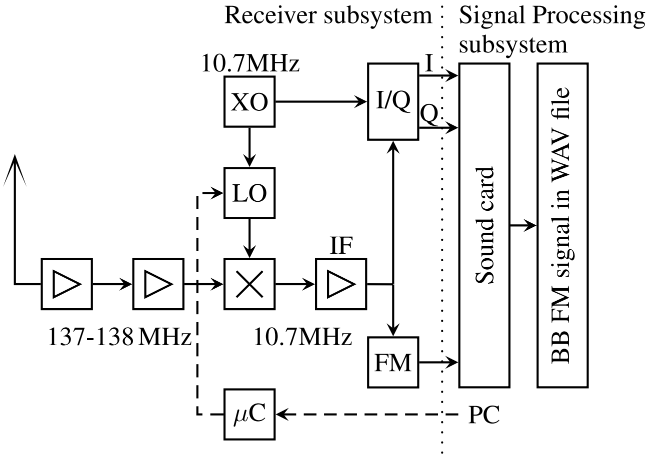

Fig. 4. Receiver subsystem

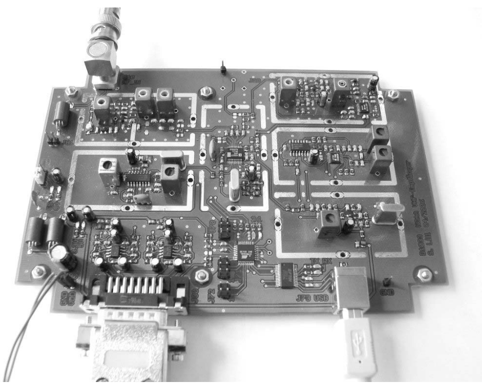

Fig. 5. Receiver hardware: Easily visible are the antenna connector on the upper left and the connectors for power, sound card, and USB on the lower side of the board. The size of the board is $175 \times 120\,\mathrm{mm}^2$.

from [3]. The next step is a DC offset compensation. DC offset arises due to a frequency mismatch of the local oscillator or a Doppler shift in connection with the FM demodulation. Simple methods of DC compensation are average removal or notch filter. Then we again apply a lowpass filter with the corner frequency 4.8 kHz before we perform the digital AM demodulation. For a simple square-law detector as an AM demodulator, the noise shaping by the lowpass filter is very important. After the AM demodulation, the APT lines as shown in Fig. 1 are available. A correlation based synchronization algorithm finds the line synchronization signals for image A and image B. The corresponding signal parts are converted to two image lines. Finally, two weather images are composed from the image lines. One of them is shown in Fig. 3.

4.2. Localization of the receiving antenna

A second signal processing task based on the same baseband satellite signals is the localization of the receiving antenna

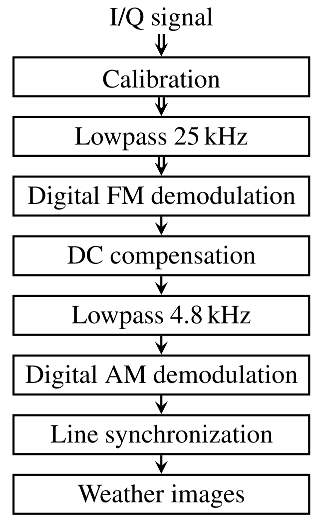

Fig. 6. Signal processing flow of weather image reconstruction. Single and double lines stand each for real and complex I/Q signal, respectively.

by using the Doppler shift. As the satellite flies over the observer, the measured satellite signal receives a Doppler frequency shift. This shift depends on the current location and flight direction of the satellite and the location of the receiving antenna. During a 15 minutes satellite pass, the Doppler shift varies in time. This Doppler shift function is unique for the antenna position except for a mirror position with respect to the plane defined by the satellite orbit. As the motion state of the satellite can be well predicted by the known orbit parameters from the internet, the task of localization is reduced to estimating the Doppler shift from the baseband signal and estimating the location of the receiving antenna from the Doppler measurements.

Several algorithms exist for the Doppler frequency estimation. A simple method is to extract the DC offset after the FM demodulation. As explained in the previous subsection, the DC offset of a FM demodulated signal depends on the frequency mismatch. A second alternative is to count the number of zero crossings. We use a more robust algorithm which correlates the spectrum of the received baseband signal with the expected spectrum of an ideal FM signal, see Fig. 7.

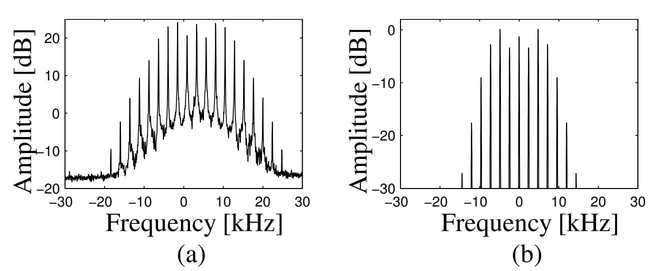

Fig. 7. a) Spectrum of a received FM signal. b) Spectrum of an ideal FM sigal

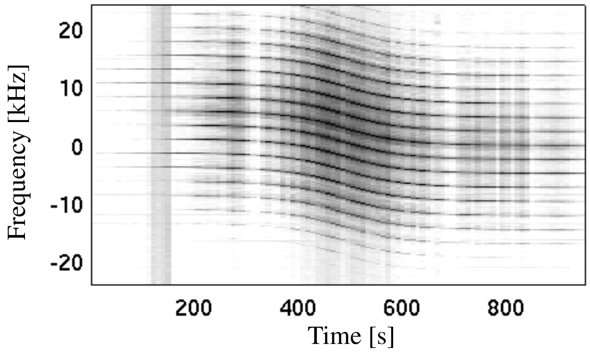

Fig. 8. Spectrum of a received FM signal over time

Fig. 8 shows the spectrum of a received FM signal over time. The middle most strong curve represents the FM carrier frequency. The Doppler shift causes the characteristic "s-shape" of the curve. At the beginning of a satellite pass, the Doppler shift is positive because the satellite is approaching the observer. At the end, the Doppler shift becomes negative because the satellite flies away. The ensemble of the "s-shape" curves is due to the Bessel function of the FM modulation, with the AM carrier contribution standing out. The maximum Doppler shift is roughly 3 kHz.

For the second step of localization from the Doppler estimates, we applied an iterative least squares approach. Given an initial guess of the antenna location, we look for an improved location estimate in its neighbor by minimizing a weighted squared error between the measured Doppler shift and its expected one which depends on the antenna location. When we use only a single satellite pass, there is an ambiguity in localization due to a mirror location with respect to the satellite orbit. The localization accuracy is 15-20 km. When we, however, use more than one satellite pass (e.g. up to five), the ambiguity is resolved and the accuracy is improved to 5 km. This performance is comparable to that of the commercial system SARSAT [4]. Currently, the main limitation in accuracy is caused by the time uncertainty of the PC clock.

4.3. Additional signal processing tasks

The main advantage of our weather satellite based platform is its open concept for signal processing. It allows us to formulate a large number of additional signal processing tasks. Below we briefly describe two of them due to limited space:

Image processing Starting with the computed weather images, students may experiment with different image processing methods and algorithms. Examples are different image enhancement filters, segmentation and land mass recognition, and overlay of images.

Array processing By using more than one receiving antenna, students have the possibility to learn and work with different array processing algorithms like beamforming and direction estimation.

5. USE IN SIGNAL PROCESSING EDUCATION

We use our weather satellite based platform for both demonstration and a project laboratory course. In the latter case, students who participate work together in small teams on a given number of signal processing tasks. The receiver subsystem is fixed and available to all students. They can use it to acquire current weather image, when one of the NOAA satellites flies over, or work with a large number of prerecorded weather images in WAV format. For each signal processing task, the reference solution we have described previously is not available to the students. Instead, we provide them with ideas, hints, and literature on how to solve the problem. The objective of the laboratory course is that students learn how to search and study literature, design the signal processing flow, select the appropriate algorithms, implement them in MATLAB, apply them to the recorded signals, and evaluate the results. Also a written report and an oral presentation are mandatory for each team. In addition, there is a competition among different teams. These teams who best solve the given signal processing problems will receive a prize.

6. SUMMARY

A weather satellite based platform for demonstration and education in digital signal processing is presented. The open concept of signal processing based on weather satellite signals offers a large degree of freedom for signal processing for students and by students. This platform is used in our project laboratory course. The varying complexity of different signal processing tasks makes this platform useful for students of different classes.

The authors would like to thank all students who participated in developing this weather satellite based signal processing platform, especially Sven Lill, Patrick Häcker, and Thomas Handte, for their valuable contributions.

7. REFERENCES

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