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A Doppler Effect Correction Method for APT Weather Satellite Image Reception

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***Abstract*—To receive an useful APT image from the NOAA weather satellites usually spends at least 10 minutes. It suffers from Doppler shift and noise due to long receiving time. In this paper, we propose a linear regression method to estimate the length of each line of the APT image, then, apply the interpolation to mitigate the Doppler shift and noise. We develop a complete APT image reception and processing system based on low cost software defined radio RTL-SDR and Matlab. An APT image was received and decoded successfully.**

***Keywords*—Doppler, weather satellite, APT signal, linear regression, spline**

I. Introduction

Weather satellite image is very useful in our daily life, it shows the cloud distribution in the sky and can be used to predict the trajectory of a tropical storm such as typhoon. The National Oceanic and Atmospheric Administration (NOAA) of America launched series of weather satellites known as NOAA-N to monitor oceanic and atmospheric conditions and forecast weather. The AVHRR image sensors are equipped onboard to take the visible and infrared pictures for the daytime and nighttime, respectively. Then, the automatic picture transmission (APT) [1][2] system is used to transmit analog images to the ground.

Citizens can use software defined radio (SDR) and software packages to receive and decode the APT signals into images [3]. Many authors received and decoded APT images successfully in different locations around the world [3]-[6]. [4] uses an RTL-SDR dongle with a double-cross dipole antenna to receive the NOAA-19 APT signal and an off-the-shelf software package is used to decode the image. The link budget issue is the focus of the paper. [5] uses the same dongle with a quadrifilar helicoidal antenna (QFH) to receive the NOAA series APT signals and decodes the image with proprietary Matlab code. The functionality of receiver is disclosed but lack of the details of algorithms and key parameters. The APT image was received and decoded successfully using in-house C++ code [6]. The decoding method was not published.

It is straight forward to receive the APT signal from the NOAA-N satellites compared to decoding of image. In this paper, we propose a method to correct the Doppler effect and noise and present the details about the signal processing.

II. Problem Formulation

A. APT signal

An APT image consists of many one-dimensional analog image signal lines, each line represents a scanned line of the surface on the earth. Synchronization pattern is prepended in each line before transmission. Sync A and B patterns are used for visible and infrared images, respectively. The APT image is first modulated as a 2.4-kHz AM signal, then modulated again as an 137.1-MHz FM signal. The well-known FM and AM demodulators can use to receive the signal into one-dimensional analog image signal lines as shown on the upper part in Fig. 1. It is clear that every Sync A is leading in front of an analog visible image line, then a Sync B is leading an analog infrared image line, repeatedly. To reduce the complexity, only a Sync A matched filter is implemented and its output signal is shown on the lower part in Fig. 1.

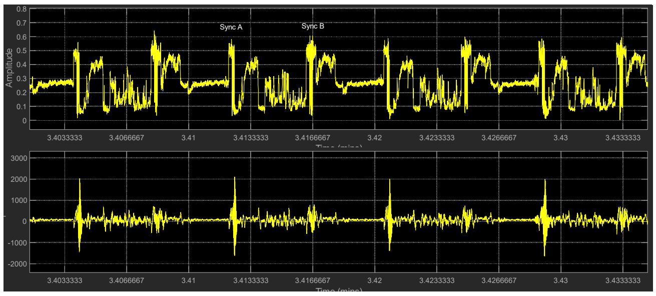

Fig. 1. Upper: The one-dimensional analog APT image signal lines, Lower: The output of Sync A matched filter.

B. Doppler Effect

The NOAA-19 is a polar orbiting weather satellite, the flying height is between 846 and 866 km above sea level. To receive a 10-minute weather imagery at a fixed location, the relative speed is within ± 6.7 km/s. The Doppler shift can be estimated by (1) and is within ± 3 kHz.

$$\boxed{f_d = \frac{v f_c}{c}} \tag{1}$$

where f_d is the Doppler shift, v is the relative speed of the satellite, f_c is the carrier frequency and c is the light speed.

There two effects on the received APT signal. First, the carrier frequency will offset around the nominal carrier frequency. Fortunately, the FM demodulator is capable of tracking the Doppler shift. The second effect is on the baseband signal, it will change the length of an received image line. As shown in Fig. 2, the length of a row in the received image is getting longer for a north bound satellite due to its Doppler shift is varying from positive to negative. The problem can be model as following. Let's represent the length of an received image line as the width of a rectangular pulse

$$\Pi(t) = \begin{cases} 1, & t \le \frac{1}{2} \\ 0, & t > \frac{1}{2} \end{cases}. \tag{2}$$

For a zero Doppler shift, the length equals to one. For non-zero case, the length is changed to α. Apply the scaling property of the Fourier transform pair to (2), we obtain

$$\Pi(\alpha t) \xleftrightarrow{\Im} \frac{1}{\alpha}\mathrm{sinc}(\frac{f}{\alpha}) \tag{3}$$

negativo si x > 1 y positivo si x < 1

where $\text{sinc}(x)$ is defined as $\sin(\pi x)/\pi x$. From (3), we know that a positive Doppler shift will narrow the bandwidth of a baseband signal and results in a shorter length of an received image line. On the other side, a negative Doppler shift will expand the bandwidth of a baseband signal and results in a longer length of an received image line. Overall, a distorted image is received in a trapezoidal-like shape in Fig. 2.

III. The Proposed Method

In this paper, we propose a linear regression method to estimate the length of each line of the APT image, then, apply the interpolation to mitigate the Doppler shift.

A. Estimation of Line Length

Define the first line of the received image as the line at bottom in Fig. 2. The Sync A is shown as the interleaved black and white pattern on the left-hand side. Due to the Doppler effect and noise, the length variation is observed in Fig. 3 and its offset are listed in Table I for some Doppler shift cases. The curve should be simply just a line if only the Doppler is effective. The receiver noise results in the detection failure of Sync A and the length varies as random spikes in Fig. 3. For simplicity, we propose to apply the linear regression to estimate the length of each line. The detection failure of Sync A pattern is conquered.

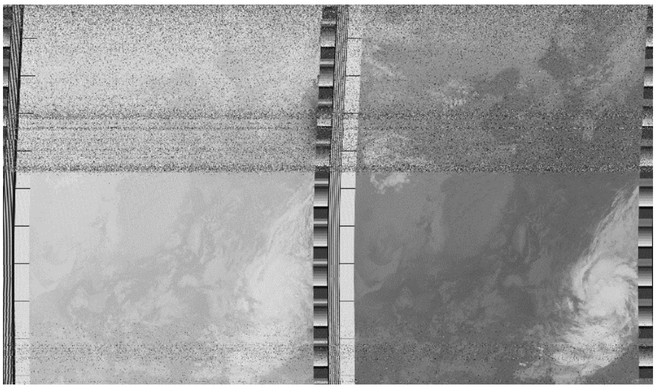

Fig. 2. The received APT image with Doppler effect.

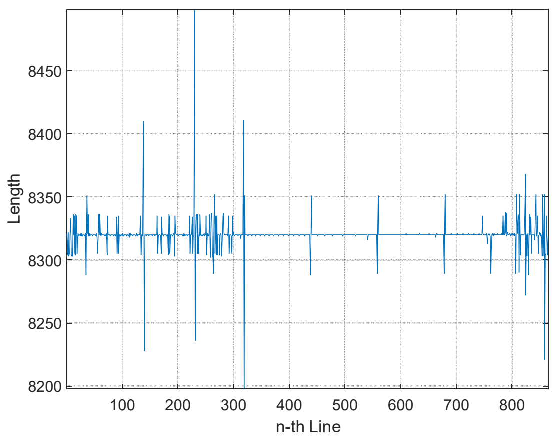

Fig. 3. Length variation due to Doppler shift and noise.

B. Shape Reconstruction

After linear regression, the shape of image becomes a typical trapezoidal. Each line should be normalized to same length. Any interpolation or resampling method can be apply to recovery the shape into a rectangle. Interpolation is more suitable for the block based line signal. We choose the cubic spine interpolation to mitigate the Doppler shift.

TABLE I. Pixel Offset by Doppler Effect

Doppler Shift (Hz)	α	Offset (Pixel)
3026	0.978	−179.7
−24	1.001	−0.8
−2199	1.015	131.2

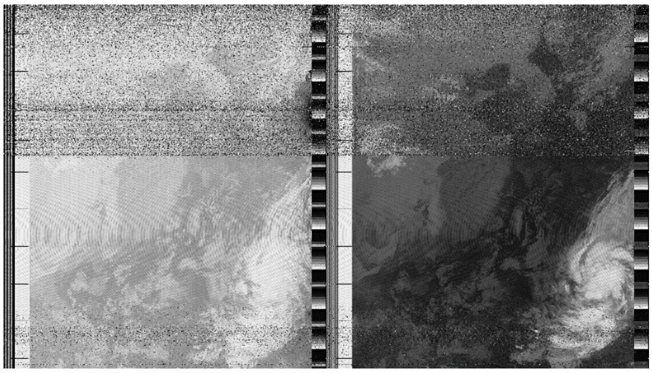

Fig. 4. The APT image after applying the proposed Doppler correction method.

IV. Results

We used a QFH and an RTL-SDR to receive the APT signal of NOAA-19 at the campus of NKUST in Taiwan on Nov. 16, 2019. The sampling rate of SDR is 1.024 Msps. SDRSharp is used to record and demodulate the FM signal of APT into a 32-Ksps AM signal for image decoding. Matlab and Simulink are used to implement the proposed method. If we didn't apply any processing to mitigate the Doppler effect and noise, the image is distorted as shown in Fig. 2. Apply the proposed method, the image is perfectly reconstructed as a rectangle as shown in Fig. 4. Each line is normalized to 8320 pixels. Furthermore, we also apply the histogram equalization to enhance the image. Typhoon Kalmaegi is clear shown in the bottom-left corner. The result provides a better image to analysis the weather condition. A complete mathematical is formulated in detail to promote the research of weather satellites imagery.

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