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The Effects of Doppler Shift on DOA Estimation in TDRSS and its Compensation Method

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Abstract

In the reverse link of Tracking and Data Relay Satellite System (TDRSS), Doppler effects in Frequency-Division Multiplexing (FDM) signal cause different frequency shift in different channels. In this work, it analyzes the influence of Doppler effects among FDM channels and establishes a mathematical model of Direction of Arrivals (DOA) estimation error while existing different frequency shift among channels. The results show that different frequency shift impacted on the correctness of DOA estimation: the direction of signals and MUSIC spectrum change periodically and non-uniform frequency shift can ruduce spectral peak. This paper proposes an improved PLL based on Extend Kalman Filter (EKF) to compensate Doppler shift between channels. The final sumulation prove that the improved PLL can correct the non-uniform frequency shift.

***Keywords**: TDRSS, DOA, Doppler Shift, MUSIC, EKF*

1. Introduction

The reverse link of Tracking and Data Relay Satellite System (TDRSS) is used to transmit data from user satellites to ground stations. Usually, Tracking and Data Relay Satellite (TDRS) use phased array antennas to track and forward multitargets. In order to reduce the payload and processing work of satellite, ground Digital Beam-Forming (DBF) is used frequently [1-2]. In this system, there are 30 independent array elements on TDRS and the datas of 30 array elements are sent to ground station through FDM scheme. Then DOA estimation and DBF can be realized to enhance the SNR of received signals at the ground station.

Doppler effect is common in wireless communication especially satellite communication system[3]. Although TDRS is on geostationary orbit, the existing small inclination can cause relative motion between the satellite and earth. As the communication frequency is very high (Ka band is used in the reverse link of TDRSS), the frequency shift of carrier can't be ignored. For FDM scheme, there are 30 carriers, and every channel gets different frequency offset. The DOA estimation accuracy can be influenced badly due to the additional frequency offset in every channel, it can become worse as time passes.

DOA estimation accuracy is influenced by the number of the snapshots, array elements, and the SNR values *etc*. MUSIC algorithm is classical and performances well [6]. For subspace-based algorithms, array sensors' position error may severely influence the estimation result [7]. To reduce the influence and promote the performance, there are many enhanced DOA estimation algorithms or methods [8] [9] [10]. But in the background of TDRSS, there are few papers considering the influence on DOA estimation as the using of FDM scheme. In [11], multi-channel group delay distortion is put forward,

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which has an impact on the performance of TDRSS. AM/PM conversion is also a error source to DOA estimation in TDRSS [12].

This study is motivated by the fact that previous studies [11] [12] didn't consider the Doppler effects in the reverse link of TDRSS. This paper is organized as follows. In Section 2, TDRSS model with Doppler Shift is established, and it makes a detailed introduction of mathematical derivation of MUSIC algorithm with different Doppler Shift in every channel. Section 3 proposes the compensation method with the structure of improved carrier tracking loop based on Kalman Filter.

Sections 4 simulates the reverse link of TDRSS and analyzes the influence to DOA estimation with different Doppler Shift and the effect of compensation. Section 5, as the conclusion part, analyzes the results of the simulation. It shows that absolute Doppler Shift and relative Doppler Shift can bring the same effects to DOA estimation, and our compensation method is effective to improve the performance of DOA.

2. The Effects of Doppler Shift on DOA

2.1. Analysis of the TDRSS Model

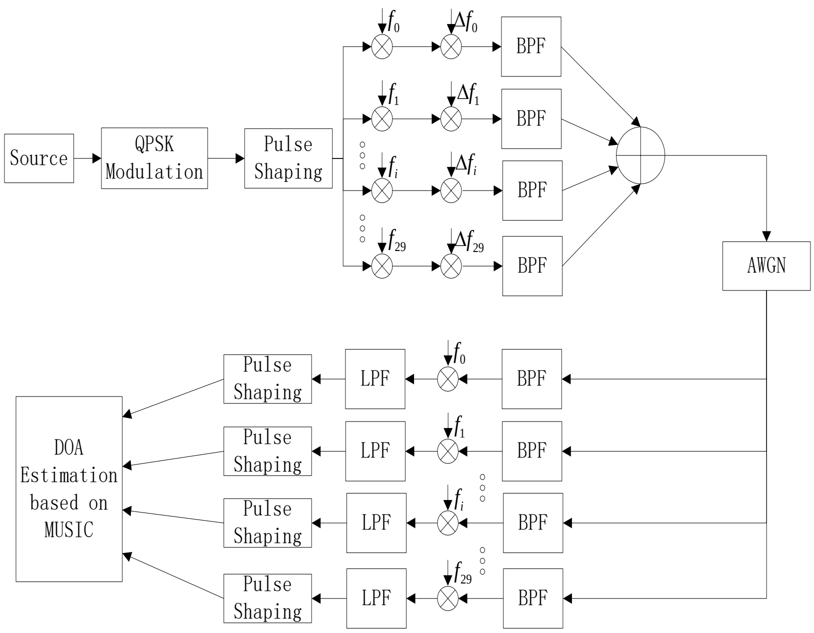


Figure 1. The System Model of Return Link in TDRSS

In order to describe the reverse link of TDRSS, we consider the model as Figure 1 shows.

We represent the input signal as $s(t)$, and the signal which the array receives can be showed as:

$$s_i(t) = s(t)e^{-j(i-1)\Delta\varphi} \tag{1}$$

Assuming the Doppler Shift on channel i is Δf_i, and the signal which is transmitted through the Satellite-Earth link can be described as:

$$x_i(t) = s(t)e^{-j(i-1)\Delta\varphi}e^{j2\pi\Delta f_i t} \tag{2}$$

So the 30 array elements signal is:

$$\mathbf{X}(t)=\left[x_0(t),x_1(t),\cdots,x_{29}(t)\right]$$
$$=s(t)\left[e^{j2\pi\Delta f_0 t},e^{j2\pi\Delta f_1 t}e^{-j(2-1)\Delta\varphi},\cdots,e^{j2\pi\Delta f_{29}t}e^{-j(30-1)\Delta\varphi}\right] \tag{3}$$

The abbreviation of formula (3) is:

$$\mathbf{X}(t)=\mathbf{D}(t)\mathbf{A}(\theta)s(t) \tag{4}$$

And:

$$\mathbf{D}(t)=diag\left[e^{j2\pi fd_0 t},e^{j2\pi fd_1 t},\cdots,e^{j2\pi fd_{29}t}\right] \tag{5}$$

fd_0, $fd_1 \ldots fd_{29}$ are the Doppler Shifts in every channel. Matrix $\mathbf{D}(t)$ reflects the phase rotation caused by Doppler Shift during the transmission. $\mathbf{A}(\theta)$ is the direction matrix. Considering the effect of Gauss white noise, formula (4) can be rewritten as:

$$\mathbf{X}(t)=\mathbf{D}(t)\mathbf{A}(\theta)s(t)+\mathbf{n}(t) \tag{6}$$

After the remote transmission by FDM method, $\mathbf{D}(t)$ exists in formula (6). Doppler Shift can bring phase error to output signals, which can also make the performance of DOA worse.

2.2. Analysis of DOA Estimation based on MUSIC

In formula (6), if we ignore the Doppler Shift in every channel, then $\mathbf{D}(t)=\mathbf{I}$. Considering the influence of Doppler Shift, $\mathbf{A}(\theta)$ changes to $\mathbf{D}(t)\mathbf{A}(\theta)$. So in the spectrum function of MUSIC algorithm, if we use $\mathbf{D}(t)\mathbf{A}(\theta)$ instead, there must be error direction. Actually, the covariance matrix is:

$$\hat{\mathbf{R}}_{\mathrm{XX}}=\mathbf{D}(\mathbf{t})\mathbf{R}_{\mathrm{XX}}\mathbf{D}^{\mathbf{H}}(\mathbf{t}) \tag{7}$$

And :

$$\mathbf{D}(t)=diag\left[e^{j2\pi fd_0 t},e^{j2\pi fd_1 t},\cdots,e^{j2\pi fd_{29}t}\right]$$
$$=e^{j2\pi fd_0 t}diag\left[e^{j0},e^{j2\pi(fd_1-fd_0)t},\cdots,e^{j2\pi(fd_{30}-fd_0)t}\right]$$
$$=e^{j2\pi fd_0 t}diag\left[e^{j0},e^{j2\pi\Delta f_1 t},\cdots,e^{j2\pi\Delta f_{29}t}\right]$$
$$=e^{j2\pi fd_0 t}\mathbf{D}' \tag{8}$$

Δf_1、$\Delta f_2 \ldots \Delta f_{29}$ are the relative Doppler Shifts between reference channel and other channels.

So:

$$\hat{\mathbf{R}}_{\mathrm{XX}}=\mathbf{D}(\mathbf{t})\mathbf{R}_{\mathrm{XX}}\mathbf{D}^{\mathbf{H}}(\mathbf{t})=\mathbf{D}'(\mathbf{t})\mathbf{R}_{\mathrm{XX}}\mathbf{D}'^{\mathbf{H}}(\mathbf{t}) \tag{9}$$

Therefore, only the relative Doppler Shift can have an effect on the performance of DOA estimation.

$$\mathbf{R_{XX}} = E\left[\mathbf{X}(\mathbf{t})\mathbf{X^H}(\mathbf{t})\right] = \mathbf{A}(\boldsymbol{\theta})\mathbf{R_{ss}}\mathbf{A^H}(\boldsymbol{\theta}) + \sigma^2\mathbf{I} \tag{10}$$

$\mathbf{R_{XX}}$ is the covariance matrix when there is no Doppler Shift, and $\mathbf{R_{ss}} = E\left[s(t)s^H(t)\right]$ is the correlation matrix of the source.

In order to facilitate the analysis,we consider the DOA estimation with one source. Eigenvalue $\{\lambda_0, \lambda_1, \cdots, \lambda_{29}\}$ can be calculated with eigen-decomposition of $\hat{\mathbf{R}}_{\mathbf{XX}}$. And it's corresponding eigenvector is $\{e_0, e_1, \cdots, e_{29}\}$.

Thus:

$$\mathbf{A^H}(\boldsymbol{\theta})\mathbf{D^H}(\boldsymbol{\theta})e_j = 0 \quad j = 1, 2, \cdots 29 \tag{11}$$

The actual spectrum of MUSIC is:

$$P = \frac{1}{\mathbf{A^H}(\boldsymbol{\theta})\mathbf{E_N}\mathbf{A^H}(\boldsymbol{\theta})} \tag{12}$$

$\mathbf{E_N}$ is the orthogonal projection matrix of noise space:

$$\mathbf{E_N} = \sum_{j=1}^{29} e_j e_j^H = \mathbf{E} - \frac{\mathbf{D}(\mathbf{t})\mathbf{A}(\boldsymbol{\theta_0})\mathbf{A^H}(\boldsymbol{\theta_0})\mathbf{D^H}(\mathbf{t})}{\sqrt{30}} \tag{13}$$

So:

$$\mathbf{A^H}(\boldsymbol{\theta})\mathbf{E_N}\mathbf{A}(\boldsymbol{\theta}) = N - \frac{\left|\mathbf{A}(\boldsymbol{\theta})\mathbf{D}(\mathbf{t})\mathbf{A^H}(\boldsymbol{\theta_0})\right|^2}{\sqrt{30}} \tag{14}$$

Besides:

$$\left|\mathbf{A}(\boldsymbol{\theta})\mathbf{D}(\mathbf{t})\mathbf{A^H}(\boldsymbol{\theta_0})\right| = \left|\sum_{i=0}^{29} \exp\left(j2\pi\Delta f_i t\right)\exp\left[j\left(2\pi d/\lambda\right)\left(\sin\theta_0 - \sin\theta\right)\right]\right| \tag{15}$$

θ_0 is the real direction of source, and θ is the direction estimated by MUSIC. In formula (15), usually at the effect of Doppler Shift Δf_i, the estimation direction is not the real direction. That is to say the disagree of Doppler Shift between channels can lead to the error of DOA.

3. Compensation Method of different Doppler Shift

In the reverse link of TDRSS, FDM method which brings 30 array elements signals back to earth can also produce additional Doppler Shift. And according to the above mentioned analysis, the absolute Doppler Shift and relative Doppler Shift can bring the same results to DOA estimation.

From (6), the receive signal can be written as:

$$y_i(t) = s(t)e^{-j(i-1)\Delta\varphi}e^{j2\pi\Delta f_i t} + n_i(t) \tag{16}$$

The SNR of receive signal, and the Doppler Shift in every channel are small (much less than spreading code rate). Since PLL (phase locked loop) is used in carrier tracking frequently, and its theories and technologies are mature, we take PLL as the basic structure in our compensation method. Different from traditional carrier tracking loop, we don't have local carrier, but we regard the receive signals as "local carrier", which can be used to track the signal of reference channel. As Extended Kalman Filter can realize nonlinear filtering and have good performance in low SNR environment, we use Extended Kalman Filter instead of loop filter in PLL. And MF (mean filter) is added before Kalman Filter to make the observation value more smooth. Figure 2 is the improved PLL.

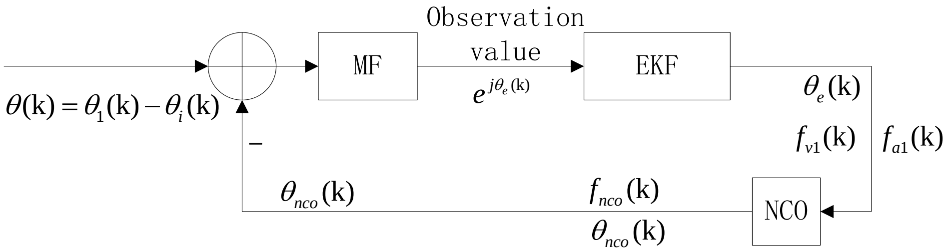


Figure 2. Improved PLL Based on EKF

In our compensation method, reference signal (set as channel 0) is mixed with other signals, and $e^{j\theta_{nco}(k)}$ comes from NCO. Phase difference signal is filtered by mean filter and sent to EKF as observation value. So the measurement equation can be:

$$y_k = e^{j\theta_e(k)} + v_k \tag{17}$$

In EKF, $x_k = \left[\theta_e(k), f_{v1}(k), f_{a1}(k)\right]^T$ is the quantity of state. The relationship among phase, frequency shift and frequency changing rate can be written as:

$$\theta(k+1) = \theta(k) + f_{v1}(k)T_s + \frac{f_{a1}(k)T_s^2}{2} \tag{18}$$

$$f_{v1}(k+1) = f_{v1}(k) + f_{a1}(\mathrm{k})\mathrm{T}_s \tag{19}$$

$$f_{a1}(k+1) = f_{a1}(k) \tag{20}$$

The update function of NCO can be described as:

$$\theta_{nco}(k+1) = \theta_{nco}(k) + \Delta\theta_{nco}(k) + f_{nco}(k)T_s \tag{21}$$

From (18) and (21), the phase difference can be:

$$\begin{aligned}\theta_e(k+1) &= \theta(k+1) - \theta_{nco}(k+1)\\ &= \theta(k) + f_{v1}(k)T_s + \frac{f_{a1}(k)T_s^2}{2} - \left(\theta_2(k) + \nabla\theta_{nco}(k) + f_{nco}(k)T_s\right)\\ &= \theta_e(k) + f_{v1}(k)T_s + \frac{f_{a1}(k)T_s^2}{2} - \nabla\theta_{nco}(k) - f_{nco}(k)T_s\end{aligned} \tag{22}$$

Combine with (19) (20) (21), the equation of state is:

$$x_k = Ax_{k-1} + Bu_{k-1} + w_{k-1} \tag{23}$$

The state transition matrix is:

$$A=\begin{bmatrix} 1 & T_s & T_s^2/2 \\ 0 & 1 & T_s \\ 0 & 0 & 1 \end{bmatrix} \tag{25}$$

Input matrix B is:

$$B=\begin{bmatrix} -1 & T_s \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{26}$$

Input signal u_k is:

$$u_k=\begin{bmatrix} \nabla\theta_{nco} \\ f_{nco} \end{bmatrix} \tag{27}$$

w_k is the noise vector of state.

As so far, we have the measurement equation and state equation of EKF. Through the procedure of prediction and correction, the state variables can be updated. With the output of NCO, channels with relative Doppler shift can be corrected.

4. Simulation and Analyze

4.1. System Model and Simulation Parameters

According to the Doppler Shift calculating model in [15] and the TLE (two line element) of TIANLIAN 1-01 [16], we calculate the Doppler Shift between TDRS and five typical Chinese cities. Table 1 lists the geographical information of the five cities.

Table 1. Geographical Coordinates of 5 Cities in China

City	Beijing	Mohe	Sanya	Wulumuqi	Xichang
Longitude(deg)	116.417	122.37	109.5	87.36	102.16
Latitude(deg)	39.9167	53.48	18.2	43.46	27.54
Altitude(km)	0	0	0	0	2

To meet the demand of high transmit rate, Ka band is used in the reverse link of TDRSS. Therefore we set carrier frequency as $f_0 = 26GHz$. Figure 3 shows the Doppler Shift between ground station and TDRS in 24 hours. From Table 2, the max Doppler Shift between ground station and TDRS can reach ±800Hz.

To be efficiency, we simulate the performance of DOA estimation with 10 channels.

In accordance with the demand of the reverse link in TDRSS, we set the SNR=10dB, direction of signal is 0° , and spreading code rate is 3MHz. Then the performance of DOA is simulated with 3 situations: no Doppler Shift, absolute Doppler Shift and relative Doppler Shift. Table 3 lists the value of Doppler Shift in 3situations.

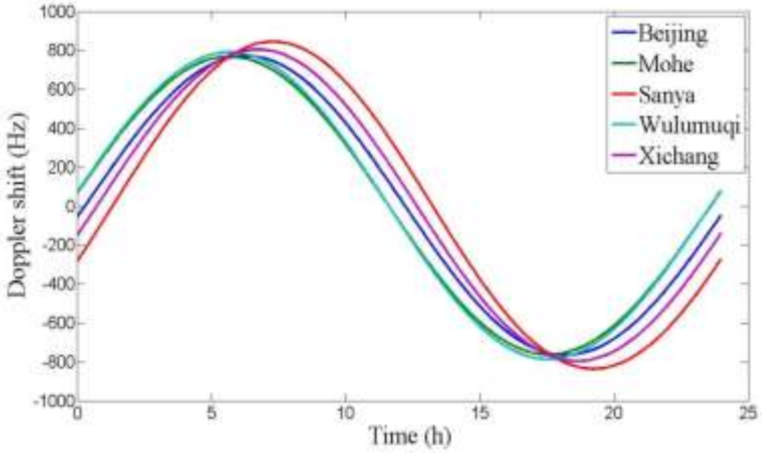


Figure 3. Doppler Shift between TDRS and 5 Cities in China

Table 2. The Maximum Doppler Shift in both Positive and Negative

City	Beijing	Mohe	Sanya	Wulumuqi	Xichang
Positive (Hz)	771.512	766.978	843.816	790.115	804.096
Negative (Hz)	765.925	763.154	836.713	787.305	797.077

Table 3. Doppler Shift in 3 Situations

Channel	No Doppler shift (Hz)	Absolute Doppler shift (Hz)	Relative Doppler shift (Hz)
0	0	700	0
1	0	710	10
2	0	720	20
3	0	730	30
4	0	740	40
5	0	750	50
6	0	760	60
7	0	770	70
8	0	780	80
9	0	790	90

4.1.1. Simulation Results in 3 Situations

According to the system model and parameters, MATLAB is adopted to build a simulation model. Figure 4, 5, 6 show the performance of DOA estimation with both 3D and 2D views. As shown in the three figures, when there is no Doppler Shift, MUSIC can estimate the direction of signals correctly. When absolute Doppler Shift is added to channels, MUSIC fails to estimate the correction direction and the estimation direction changes periodically. Figure 6 shows the same results with Figure 5, therefore relative

Doppler Shift can bring the same influence as absolute Doppler Shift to estimation performance. It confirms the analysis in part 2.

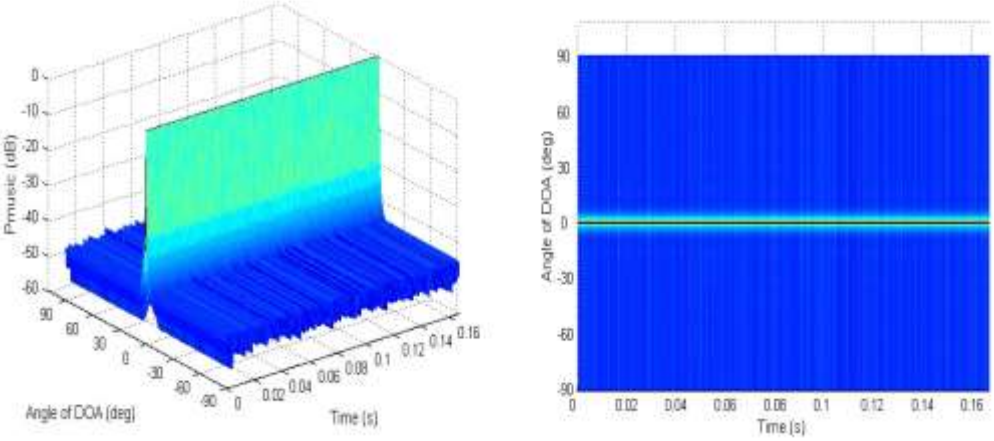


Figure 4. No Doppler Shift

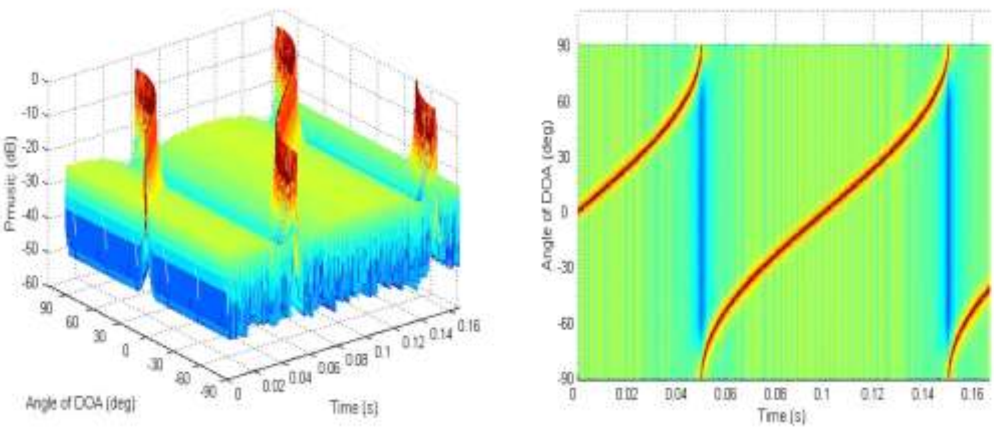


Figure 5. Absolute Doppler Shift

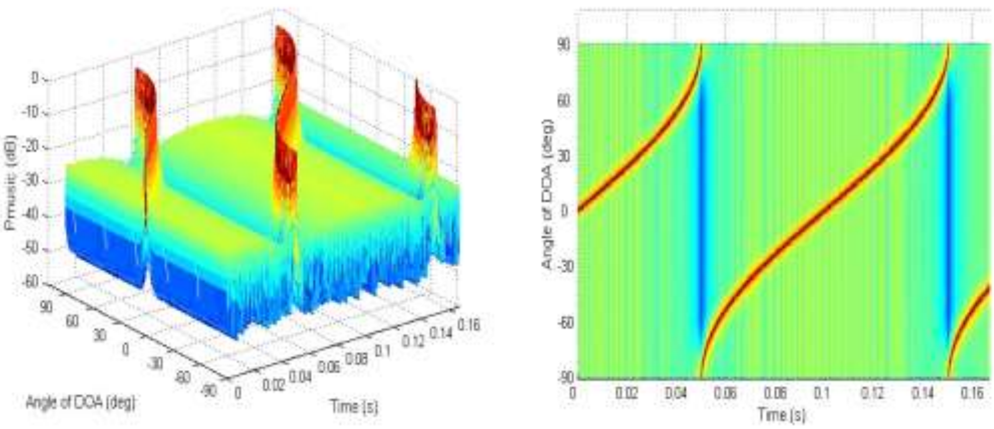
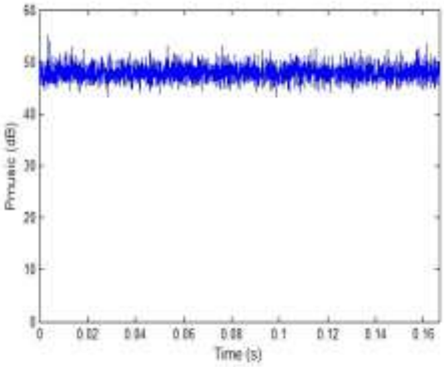
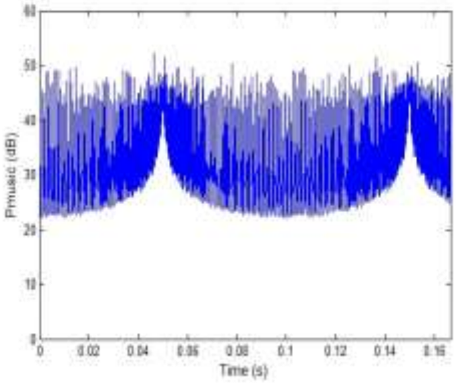


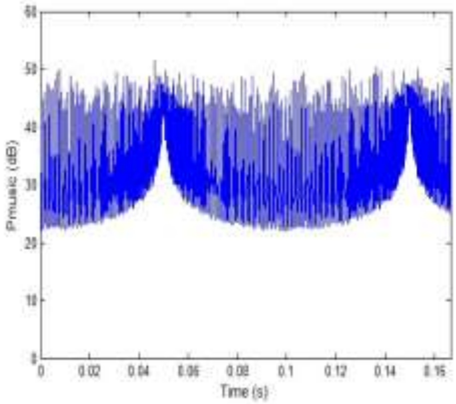
Figure 6. Relative Doppler Shift



(a)



(b)



(c)

Figure 7. Spectrum of MUSIC

In Figure 7, (a) (b) (c) show the spectrum of MUSIC as time goes by in three situations: no Doppler Shift, absolute Doppler Shift and relative Doppler Shift. The spectrum height is stable at nearly 50dB when there is no Doppler Shift. However different Doppler Shift in channels can make the spectrum fluctuate in a large range (22~50dB), and they also show the periodicity.

Figure 8 shows the phase difference (after MF) between channel 1 and the reference channel (the other channels own similar character). And the period of phase difference coincides with the Doppler Shift.

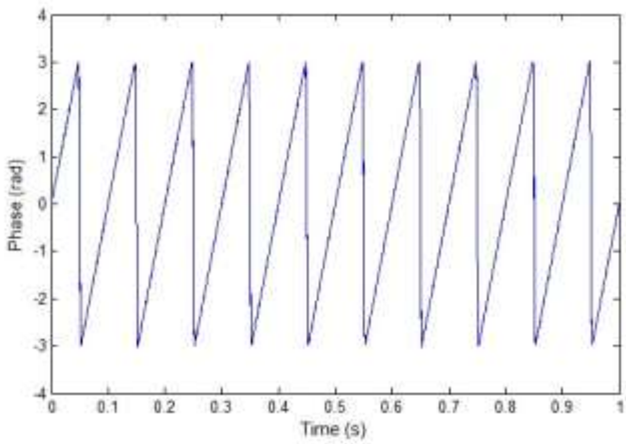


Figure 8. Phase Difference between Channel 1 and Reference Channel

4.1.2. Simulation of Compensation Method

In part 3, improved PLL which is based on EKF is introduced. This structure is added to every channel except for reference channel (channel 0 is set as reference channel).

Figure 9 shows the output (f_{v1}) of EKF. Compared with Table 3, the estimation of frequency is almost accurate. And the phase error (channel 1 and 0) is also acceptable.

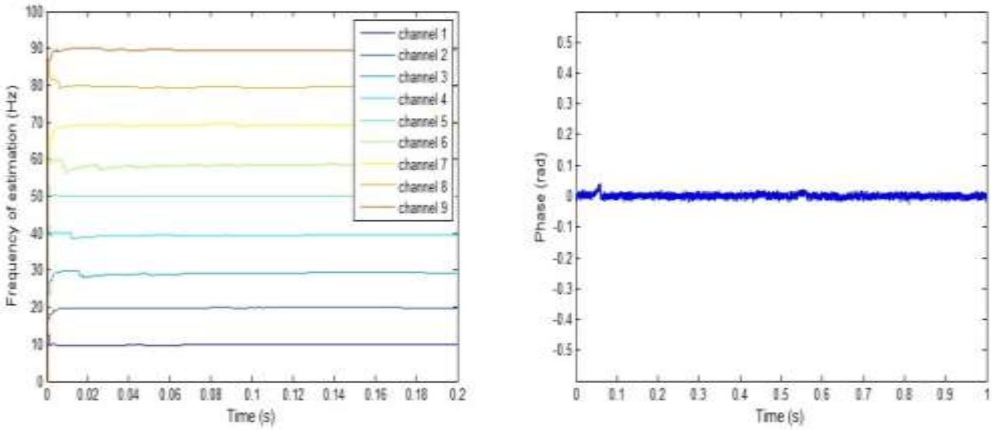


Figure 9. Estimation Frequency and Phase Error

Figure 10 and Figure 11 show the performance of DOA estimation. Compared with Figure 4, 5, 6, the direction of MUSIC is stable at 0° after the compensation. The spectrum of MUSIC is higher and much more stable than before in Figure 7 (b) (c). Because of the noise in channels and the frequency and phase error of the EKF, in Figure 11, the height of MUSIC spectrum is around 40dB, which is 10dB lower than that in Figure 7 (a).

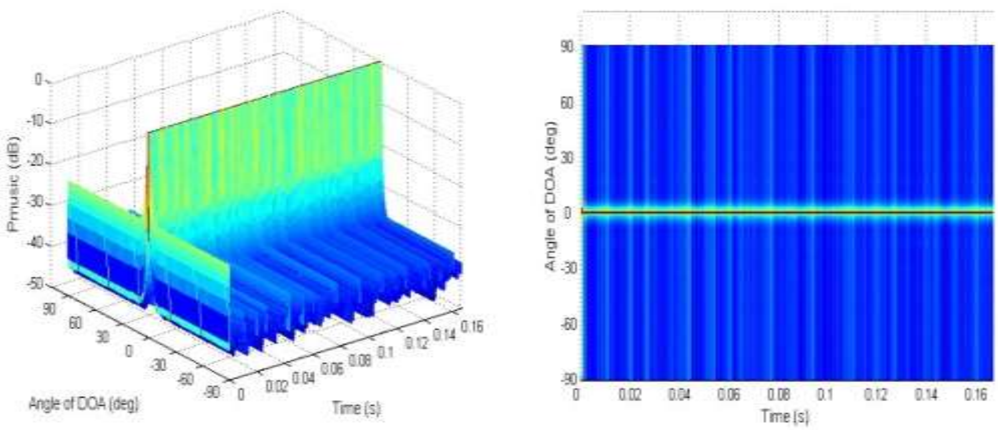


Figure 10. DOA Estimation after Compensation

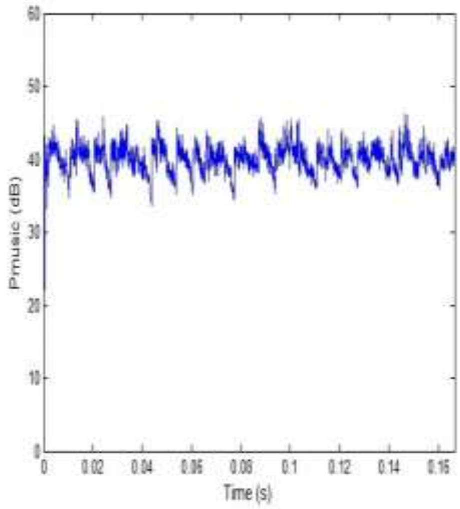


Figure 11. Spectrum of MUSIC after Compensation

5. Conclusions

In TDRSS, the FDM method is used to transfer element signals which are received on satellite to the ground station. Relative motion between satellite and ground station can bring different Doppler Shift to 30 channels. As MUSIC algorithm is sensitive to array signals phase error, Doppler Shift in channels can bring great influence on performance of DOA. Through mathematical derivation and simulation, different Doppler Shift in channels makes the estimating direction change periodically. What's more, absolute Doppler Shift and relative Doppler Shift can bring the same effects to DOA estimation and spectral peak. On the basis of that, an improved PLL based on EKF is proposed to compensate different Doppler Shift. By adding the improved PLL structure to every channel except for the reference channel, the relative Doppler Shift among channels can be compensated. Thus it can eliminate the periodical changes in DOA estimation and increase the height of spectrum peak. The theoretical deduction is verified to be correct and the compensation method is effective through computer simulation. This work researches on the problem exists in TDRSS, and may be helpful in designing next generation TDRSS. In the following study, we may improve the compensating accuracy by combining direction error of MUSIC and despreading.

Acknowledgements

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