ABSTRACT

The well-known FORMOSAT-3/COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) mission is a joint Taiwan/US science mission for weather, climate, and space weather research. The six LEO satellites constellation equipped with GPS receiver for Radio Occultation (RO) experiment has successfully provided a significant amount of RO data for numerical weather predication, weather forecasting, and space weather monitoring. Owing to the success of the FORMOSAT-3 program, a follow-on FORMOSAT-7 mission is being planned by NSPO and NOAA to develop a capability of providing operational continuity of global GNSS RO observations. In the paper, the requirements on the FORMOSAT-7 mission will be briefly reviewed. The constellation design for global coverage with sufficient temporal and spatial resolution, and the operation features for enhanced regional resolution will be described. According to the antenna limits, a single antenna cannot track the satellite over a wide range of azimuths. Furthermore, the retrieval quality depends on the RO observations. Accounting for weak signal of occultation environment, antenna array and digital beamforming approach are adopted to enhance the signal power in this paper. The Minimum Variance Distortion Response (MVDR) algorithm is used to compute the weights iteratively. Then, combine the signal of antenna array and track the signal by either closed-loop or open-loop. An experiment is conducted by receiving a real GPS satellite in low elevation angle which simulates the weakness of the occultation signal. Finally, the assessment of antenna array processing will be shown in the last segment.

KEYWORDS: Constellation Design, Radio Occultation, FORMOSAT-7, Beamforming
1. INTRODUCTION

In 1994, University Corporation for Atmospheric Research (UCAR) succeeded in GPS meteorology technique using ground GPS receivers, GPS/MET (Bevis et al., 1994). The GPS/MET experiment showed that the atmospheric sounding using GPS radio signal. Furthermore, the active sounding technique has been developed from ground based GPS meteorology to space based, such as GRACE, and CHAMP (Wickert et al., 2009). The successful GPS RO (Radio Occultation) space missions provided the high accuracy and vertical resolution atmospheric sounding, which is an important milestone in the evolution of GPS sounding techniques (Yunck et al., 2000). More and more space missions are developed and planned for GPS/MET by the Europe, Japan, and so on. However, the spatial and temporal distribution of global atmospheric sounding is restricted by the single spacecraft mission. The first operational GPS RO sounding constellation is the Formosat-3/COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) mission. The FORMOSAT-3/COSMIC provides a great leap in GPS RO techniques with data volume and quality for the global atmospheric researches and the near real time forecast, and becomes an important GPS radio occultation constellation in the world. However, the global uniform atmospheric sounding requirement is limited by current constellation configuration. In view of this, an augmentation mission, follow-on FORMOSAT-7 will improve and strengthen the current mission design. First part is to upgrade the capability GNSS RO receiver design to accommodate GNSS signals from American GPS, Europe’s Galileo, and Russian GLONASS. Furthermore, more satellite constellations could provide more densely atmospheric sounding and variety mission requirements. Nevertheless, the regional atmospheric sounding coverage should be balanced by the satellite constellation design and satellite operation. The constellation design and satellite operation are proposed, then the designed constellation RO sounding distribution simulation and enhanced regional resolution are discussed. According to the satellite operation and antenna limits, the antenna array and digital beamforming approach are adopted to enhance the signal power. Experiments are conducted by receiving a real GPS satellite to evaluate the performance of antenna array processing.

2. Constellation Design and Satellite Operation

The GNSS RO point distribution relies on the relative geometry between the GNSS satellites and observing satellite, as well as parameters associated with receiver antennas. The GNSS RO operating principle can be found in (Yunck et al., 2000). A single satellite usually recovers more than 500 profiles per day and a constellation could recover thousands of profiles, such FORMOSAT-3/COSMIC constellation. In addition to the first fully operational GNSS, GPS, other satellite based navigation systems including GLONASS from Russia, Galileo from European Union, and Compass from China, are being implemented. The follow-on FORMOSAT-7 mission design considers the following GNSS constellation: American GPS, Europe’s Galileo, and Russian GLONASS. Moreover, some SBAS (Space-Based Augmentation System) including WAAS, EGNOS, MSAS, and GAGAN satellites, due to their "GPS like" signals, are also accounted for (Juang et al., 2010). The FORMOSAT-7 mission objective is to provide 5 (objective) or 4 (threshold) daily GNSS RO profiles over any arbitrary 500 km square horizontal box. Several candidate constellations in terms of orbit inclination and altitude have been considered in (Chu et al., 2010). A refinement based on genetic algorithm has also been investigated (Juang et al., 2010). A hybrid constellation includes two LEO satellite constellations at different inclination and altitude could fulfill the requirements. The first constellation contains six satellites of inclination 240° and altitude 520
km with orbital plane separation at equator $60^0$ and the second constellation contains six satellites of inclination $72^0$ and altitude 800 km with orbital plane separation at equator $30^0$. These two satellite constellations will be deployed through two launches. The simulations of RO profile distribution are illustrated in the following figures.

Figure 1. FORMOSAT-7 RO soundings distribution with GPS constellation

Figure 2. FORMOSAT-7 RO soundings distribution with Galileo constellation
These figures indicate the low inclination satellites enable the generation of denser distribution of RO profiles in lower latitude region. Since the SBAS geostationary satellite geometry, the RO sounding distribution is like a great circle with a radius of 80 degrees and the centre of the big circle is the SBAS broadcasting satellite. In addition to SBAS, the RNSS constellations also broadcast radio signals and are available for GNSS RO mission. Two major RNSS systems proposed or under development are Quasi-Zenith Satellite System (QZSS) and Indian Regional Navigation Satellite System (IRNSS). The QZSS satellite orbit traces and RO sounding distribution is shown in Figure 5. It is noted that the satellite trace is an analemma or figure eight. Thereby, the RO sounding distribution based on RNSS...
constellation can be regarded as another big analemma, which is orthogonal with the satellite trace. Hence, these kinds of constellations configuration can be regarded as an augmentation atmospheric sounding in the distribution of RO profiles (Juang et al., 2010).

![Figure 5. FORMOSAT-7 RO soundings distribution with QZSS](image)

Since Taiwan is in the low latitude region, Taiwan is subject to the risk of severe weather such as typhoons. It means that the resolution in space and time is required to be enhanced when typhoons are approaching (Juang et al., 2011). However, the above constellation design and optimization can only fulfill the requirement on the uniform distribution in time and space. Indeed, the denser distribution of RO profiles needs more observing satellites. Therefore, a fine resolution for better prediction accuracy through additional satellites is not deemed as a cost-effective solution. In order to resolve this issue, the satellite is designed to perform attitude control to acquire GNSS RO data when the RO events take place in the interested area. Figure 6 depicts the increase of RO profiles when observing satellite operates attitude control to slew the antenna toward GNSS satellites in an attempt to increase the number of RO data points around Taiwan. The black points in the figure are the additional RO points.

![Figure 6. Increase of RO profiles around Taiwan](image)
3. ANTENNA ARRAY BEAMFORMING

The primary goal of antenna array beamforming is to enhance the carrier-to-noise ratio of desired signal. Digital beamforming approaches control the reception pattern by weighting and summing the signals of antenna array. Several algorithms are used to calculate weights. Some of them optimize certain conditions with known signal structure of the desired signal such as maximum signal-to-interference ratio, minimum mean square error and minimum output power. Others algorithms do not need prior knowledge of signal structure and minimize output power to certain constraints such as Minimum Variance Distortionless Response (MVDR) (Applebaum, 1976) and Constrained Least Mean-Squares (Frost III, 1972). The constraints can be set to form a beam in the direction of satellite or steer a null in the direction of interference. However, the steering vector associated with the direction of satellite needs to be obtained either from satellite ephemeris or carrier phase differences between elements of antenna array. Due to low power of GNSS RO signal, one adopts the Space-Time Adaptive Processing (STAP) with adaptive MVDR beamforming algorithm as shown in Figure 7.

Beamforming algorithm combines the signal of antennas, multiplied by complex weights and then summed over all antennas as equation (1).

$$y[k] = \sum_{n=1}^{N} \sum_{m=0}^{M-1} w_{nm} s_n[k-m] = W^T S[k]$$

$$W = \begin{bmatrix} w_{10} & w_{20} & \cdots & w_{N0} & w_{11} & \cdots & w_{N1} & \cdots & w_{N0} & \cdots & w_{N(M-1)} \end{bmatrix}^T$$

$$S[k] = \begin{bmatrix} s_1[k] & s_1[k-1] & \cdots & s_1[k-(M-1)] \\ s_2[k] & s_2[k-1] & \cdots & s_2[k-(M-1)] \\ \vdots & \vdots & \ddots & \vdots \\ s_N[k] & s_N[k-1] & \cdots & s_N[k-(M-1)] \end{bmatrix}^T$$

where $N$ is the number of element in the antenna array. $M$ is the number of tap. $s_n[k-m]$ is the signal from nth antenna and mth tap. $w_{nm}$ is the weight associated to the nth antenna and mth tap. The MVDR algorithm minimizes the output power and constraint the gain of the
direction of desired signal to unity as follow (Frost III, 1972).

$$\text{minimize } y^T y = W^T R W$$

subject to $W^T C = 1$ \hspace{1cm} (2)

where $R$ is the covariance matrix of input signals and $C$ is the constraint vector toward the target satellite. The covariance matrix $R$ is estimated by computing sample covariance matrix with assuming the sample mean is zero as equation (3).

$$R[k] = \frac{1}{N_s} \sum_{t=0}^{N_s-1} S[k+t]S^*[k+t]$$ \hspace{1cm} (3)

where $N_s$ is the number of samples to compute the covariance matrix. The constraint vector $C$ is composed of steering vector $T$ in the first to Nth component and zeros in the others represented in equation (4).

$$C = \begin{bmatrix} t_1 & t_2 & \cdots & t_N & 0 & \cdots & 0 \end{bmatrix}^T$$

$$T = \begin{bmatrix} t_1 & t_2 & \cdots & t_N \end{bmatrix}^T$$ \hspace{1cm} (4)

Traditionally, the signal of first antenna is set as a reference and its component of steering vector is set to 1. The other components are set as phase shifts relative to the reference antenna represented in equation (5).

$$t_i = \exp\left(-j \left( \Delta \phi^i + \Delta \gamma^i \right) \right)$$ \hspace{1cm} (5)

where $\Delta \phi^i$ is the phase difference based on antenna geometry and the direction of desired satellite. $\Delta \gamma^i$ is the phase resulting from the difference of cabling and RF chain including down converter and digitization among elements of antenna array. $\Delta \phi^i$ can be calculated as

$$\Delta \phi^i = \frac{2\pi \tilde{p}_i \cdot \hat{r}^i(\varphi, \theta)}{\lambda}$$ \hspace{1cm} (6)

where $\tilde{p}_i$ is the baseline vector of the ith antenna and $\hat{r}^i(\varphi, \theta)$ is the unit vector to satellite $l$ as shown in the Figure 8.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{antenna_geometry.png}
\caption{Antenna geometry and direction of satellite showing calculation of $\Delta \phi^i$}
\end{figure}

Assume $\tilde{p}_i$ is known and $\hat{r}^i(\varphi, \theta)$ can be obtained through positioning. Only $\Delta \gamma^i$ is needed to be re-calibrated whenever any part of hardware of antenna array is changed. The solution of (2) is

$$W = R^{-1} C \left( C^T R^{-1} C \right)^{-1}$$ \hspace{1cm} (7)
There are three matrix inversions in (7). Alternatively, (Frost III, 1972) derived an adaptive approach which iteratively updates the weight listed by (8)

\[
W[0] = \frac{1}{N} C
\]

\[
W[k+1] = \left( I - \frac{1}{N} CC^T \right) (I - \mu R[k]) W[k] + \frac{1}{N} C
\]  \hspace{1cm} (8)

where \( \mu \) is the adaptation step size which can be constant or variable related to covariance matrix. In our software receiver, \( \mu \) is calculated by equation (9).

\[
\mu = \frac{\alpha}{\text{trace}(R)}
\]  \hspace{1cm} (9)

In order to examine this algorithm, a RF front-end is used to collect multi-antenna signals. The hardware configuration of collection system is depicted as following. It consists of four antennas, a RF front-end and personal computer. In the RF front-end, the signals from the antenna are sent to four identical RF chains and the digitized by a synchronized clock. The digital IF signals are transmitted to personal computer. The collected IF signals are then processed by developed software receiver.

The software is developed with Visual Studio under 32-bit version of Microsoft Windows 7. Most of source codes are programmed using C++. The functions with high computational complexity are programmed by assembly such as correlation operation and covariance matrix calculation. The used components are listed in the Table 1 and the flowchart is shown in Figure 10. Each component would be discussed in the following sections.

Figure 9. Hardware configuration of used collection system

Figure 10. Hardware configuration of used collection system
<table>
<thead>
<tr>
<th><strong>Component</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Software correlator</td>
<td>Hand-coded inline assembly using SSE instruction set based on bit-wise parallel algorithm.</td>
</tr>
<tr>
<td>Tracking Positioning</td>
<td>Use GPL-GPS open source code and modify interface to software correlator.</td>
</tr>
<tr>
<td>MVDR adaptive beamforming -Covariance Calculation</td>
<td>Hand-coded inline assembly using SSE instruction set for calculating covariance.</td>
</tr>
<tr>
<td>-Weight Update</td>
<td>Hand-coded C++ code for weight update.</td>
</tr>
<tr>
<td>Weight-and-Sum and quantization of composite signal</td>
<td>Perform the signal combination as equation (1). Hand-coded inline assembly using SSE instruction set.</td>
</tr>
<tr>
<td>ICP initialization and calculation of the differential ICP</td>
<td>Perform the initialization and difference calculation of ICP for determining the steering vectors.</td>
</tr>
<tr>
<td>System Program</td>
<td>Arrange threads to achieve real-time capability</td>
</tr>
</tbody>
</table>

There are two antenna array arrangements. First arrangement is a linear array which is similar to the antenna array on the FORMOSAT-3 satellite is shown in the Figure 11.

![Linear antenna array](image)

**Figure 11.** Linear antenna array

The screenshot of developed software receiver is shown in the Figure 12. On that time, the software receiver performed beamforming toward PRN 2. The C/No value of beamforming channel for PRN 2 had about 6 dB gain over single antenna channel. The gain pattern shows the beamforming result which has high gain in the direction of PRN 2. However, in the other direction like PRN 15, there was low gain in the gain pattern. Moreover, the C/No of beamforming channel for PRN 15 was lower than that of single antenna. Because of the arrangement of antenna array, the gain pattern is like the shape of array and this did not have beam toward target direction.
The second antenna array arrangement is a rectangular array which distance between elements is half wavelength shown in Figure 13. Using this array, the screenshot of software receiver is shown in Figure 14. The gain pattern of this array can steer a beam toward the target satellite PRN 12; there was a gain in the C/No corresponding to gain pattern.

Figure 12. Screenshot of software receiver toward PRN 2

Figure 13. Rectangular antenna array
4. CONCLUSIONS

In this paper, the constellation design for global coverage with sufficient temporal and spatial resolution, and the operation features for enhanced regional resolution are described for the follow-on FORMOSAT-7 RO mission. Since the retrieval quality depends on the RO observations, an adaptive beamforming algorithm, Minimum Variance Distortion Response (MVDR) algorithm, is implemented to adaptively maximize signal power for the RO weak signal reception. Two types of antenna array configurations are considered by receiving a real GPS satellite and the assessment of antenna array processing are shown in this paper.

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REFERENCES


