Space-Time Equalization Techniques for New GNSS Signals

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BIOGRAPHIES

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ABSTRACT

GNSS signal processing involving BOC modulations requires tracking techniques able to provide unambiguous code tracking with reduced losses in the signal quality. Space-time processing techniques have the potential of combining the advantages of temporal equalization, for unambiguous tracking, and spatial processing for improved signal quality.

In this paper, the use of space-time processing for the tracking of new GNSS signals is considered. A new tracking technique is developed including temporal equalizers at each antenna output and a spatial filter combining the different correlator branches. The temporal equalizers are designed based on the minimum mean square error criterion whereas the spatial filter is characterized by a minimum variance distortionless response. The effectiveness of the proposed algorithm is validated using simulated and live GPS data obtained from antenna arrays with different structures and antenna spacing.

1 INTRODUCTION

New and modernized Global Navigation Satellite Systems (GNSS) such as GPS, Galileo, GLONASS and COMPASS broadcast signals with enhanced correlation properties as compared to the first generation GPS signals. New GNSS signals are characterized by different modulations that provide improved time resolution, resulting in more precise range measurements, along with the advantage of being more resilient to multipath and Radio Frequency (RF) interference (Betz 2002). One of these modulations is the Binary-Offset-Carrier (BOC) modulation transmitted by Galileo and modernized GPS.

Despites the benefits of BOC modulation schemes, difficulties in tracking BOC signals can arise. The autocorrelation function (ACF) of BOC signals is multi-peaked potentially leading to false peak-lock and ambiguous tracking. Intense research activities have produced different BOC tracking schemes that address the issue of multi-peaked BOC signal tracking [a review of different unambiguous tracking techniques can be found in (Anantharamu 2011)]. Additionally, new tracking schemes including space-time processing can be adopted to further improve the performance of existing algorithms.

Space-time equalization (Kohno 1998) is a technique that utilizes spatial and temporal information of signals received from multiple antennas to compensate for the effects of multipath fading and co-channel interference. In the context of BOC signals, these kinds of techniques can be applied to mitigate the impact of the sub-carrier, which is responsible for a multi-peaked ACF, reducing multipath
and interference effects. In temporal processing, traditional equalizers in time-domain are useful to compensate for signal distortions. But equalization becomes more challenging in the case of BOC signals when the effect of both sub-carrier and multipath has to be accounted for. On the other hand, by using spatial processing, it should be possible to extract the desired signal component from a set of received signals by electronically varying the antenna array directivity (beamforming). The combination of an antenna array and a temporal equalizer results in better system performance. Hence the main objective of this paper is to apply space-time processing techniques for BOC modulated signals received by an antenna array. The main intent is to enhance the signal quality, avoid ambiguous tracking and improve tracking performance under weak signal environments or in the presence of harsh multipath components.

Antenna array processing using GNSS signals have been demonstrated by (Seco-Granados et al. 2005, O’Brien & Gupta 2008, Vicario et al. 2010, Rougerie et al. 2011). The focus was on enhancing GNSS signal quality and mitigating interference and/or multipath related issues. Unambiguous tracking was not considered. In this paper, a space-time algorithm is developed to mitigate ambiguous tracking of BOC signals along with improved signal quality. The main objective is to obtain an equalization technique that can operate on BOC signals to provide unambiguous BPSK-like correlation function with the capability of altering the antenna array beam pattern to improve the signal to interference plus noise ratio.

Initially, temporal equalization based on the Minimum Mean Square Error (MMSE) technique is considered to obtain unambiguous ACF on individual antenna outputs. Spatial processing is then applied on the correlator outputs based on a modified Minimum Variance Distortionless Response (MVDR) approach. As part of spatial processing, online calibration of the real antenna array is performed which also provides signal and noise information for the computation of the beamforming weights. Finally, the signal resulting from temporal and spatial equalization is fed to a common code and carrier tracking loop for further processing.

The effectiveness of the proposed technique is demonstrated by simulating different antenna array structures for BOC signals. Intermediate Frequency (IF) simulations have been performed and linear/planar array structures along with different signal to interference plus noise ratios have been considered. A modified version of The University of Calgary software receiver, GSNRx™, has been used to simultaneously process multi-antenna data. Further tests have been performed using real data collected from Galileo test satellites, GIOVE-A and GIOVE-B, using an array structure comprising of two to four antennas. A 4-channel front-end designed in the PLAN group, University of Calgary (Morrison 2010) and a National Instruments (NI) signal vector analyzer equipped with three PXI-5661 front-ends (NI 2006) has been used to collect data synchronously from several antennas. The data collected from the antennas were progressively attenuated for the analysis of the proposed algorithm in weak signal environments.

From the performed tests and analysis, it is observed that the proposed methodology provides unambiguous ACF. Spatial processing is able to efficiently estimate the calibration parameters and steer the antenna array beam towards the direction of arrival of the desired signal. Thus, the proposed methodology can be used for efficient space-time processing of new BOC modulated GNSS signals.

The remainder of this paper is organized as follows: Section 2 introduces the signal and system model used for the development of the proposed space-time processing technique. Section 3 provides a brief introduction to the concept of space-time processing and methodologies adopted in the GNSS signal community. In Section 4, a detailed description of the adopted processing structure is discussed whereas simulation results and real data analysis are provided in Section 5. Finally, conclusions are drawn in Section 6.

2 SIGNAL AND SYSTEMS MODEL

The complex baseband GNSS signal vector received at the input of an antenna array can be modeled as (Anantharamu 2011)

$$\tilde{y}(t) = \begin{bmatrix} \tilde{y}_0(t) \\ \tilde{y}_1(t) \\ \vdots \\ \tilde{y}_{M-1}(t) \end{bmatrix} = \sum_{i=0}^{L-1} C_s x_i(t) + \eta(t)$$

(1)

where

- $M$ is the number of antenna elements;
- $L$ is the number of satellites;
- $C$ is a $M \times M$ calibration matrix capturing the effects of antenna gain/phase mismatch and mutual coupling;
- $s_i = [s_0 \ s_1 \ \cdots \ s_{M-1}]$ is the complex $M \times 1$ steering vector relative to the signal from the $i^{th}$ satellite. $s_i$ captures the phase offsets between signals from different antennas;
- $\eta(t) = [\eta_0(t) \ \eta_1(t) \ \cdots \ \eta_{M-1}(t)]^T$ is the noise plus interference vector observed by the $M$ antennas.

The $i^{th}$ useful signal component $x_i(t)$ can be modeled as
\[ x_i(t) = A_i d_i(t - \tau_{0,i}) c(t - \tau_{0,i}) e^{j(2\pi f_{0,i} \tau + \phi_i)} \]  

(2)

where

- \( A_i \) is the received signal amplitude;
- \( d_i(\cdot) \) models the navigation data bit;
- \( c_i(\cdot) \) is the ranging sequence used for spreading the transmitted data;
- \( \tau_{0,i}, f_{0,i} \) and \( \phi_i \) denote the code delay, Doppler frequency and carrier phase introduced by the communication channel.

The index ‘\( i \)’ is used to denote quantities relative to the \( i \)th satellite. The ranging code \( c_i(\cdot) \) is made up of several components including a primary spreading sequence, a secondary code and a sub-carrier and can be expressed as

\[ c_i(t) = \sum_{k=-\infty}^{\infty} p_i(kT_s)s_b(t - kT'_s). \]  

(3)

In Eq. (3), \( p_i(t) \) represents the combination of primary and secondary code with chip duration \( T_s \), while \( s_b(t) \) represents the sub-carrier. For a BPSK modulated signal, the sub-carrier is a rectangular window of duration \( T_s \). In the case of BOC modulated signals, the sub-carrier is generated using a sinusoidal carrier with frequency \( f_c \)

\[ f_c(t) = \begin{cases} \text{sign}(\sin(2\pi f_it)), & \text{sin BOC} \\ \text{sign}(\cos(2\pi f_it)), & \text{cos BOC} \end{cases} \]  

(4)

The presence of this sub-carrier produces a multi-peaked autocorrelation function making the acquisition/tracking processes ambiguous (Anantharamu 2011). In order to extract signal parameters such as code delay and Doppler frequency of the \( i \)th useful signal \( x_i(t) \), the incoming signal \( \tilde{y}_m(t) \) is correlated with a locally generated replica of the incoming code and carrier. This process is referred to as correlation where the carrier of the incoming signal is at first wiped off using a local complex carrier replica. The spreading code is also wiped off using a ranging code generator. The signal obtained after carrier and code removal is integrated and dumped over \( T \) seconds to provide correlator outputs. The correlator output for the \( h \)th satellite and \( m \)th antenna can be modeled as (Anantharamu 2011):

\[ q_{m,h} = \frac{1}{T} \int_0^T \tilde{y}_m(t)c_h(t - \tau_h)e^{-j(2\pi f_{D,h}t + \phi_h)} dt \]

\[ \approx \sum_{k=0}^{M-1} v_{m,k} s_h(t_k) c_h(t - \tau_h) e^{-j(2\pi f_{D,h} t_k + \phi_h)} dt + \eta_{m,h} \]  

(5)

where \( v_{m,k} \) are the coefficients of the calibration matrix, \( C \)

\[ C = \begin{bmatrix} v_{0,0} & v_{0,1} & \cdots & v_{0,M-1} \\ v_{1,0} & v_{1,1} & \cdots & v_{1,M-1} \\ \vdots & \vdots & \ddots & \vdots \\ v_{M-1,0} & v_{M-1,1} & \cdots & v_{M-1,M-1} \end{bmatrix} \]

(6)

and \( R(\Delta \tau_h) \) is the multi-peak ACF. \( \tau_h, f_{D,h} \) and \( \phi_h \) are the code delay, Doppler frequency and carrier phase estimated by the receiver and \( \Delta \tau_h, \Delta f_{D,h}, \Delta \phi_h \) are the residual delay, frequency and phase errors. \( \eta_{m,h} \) is the residual noise term obtained from the processing of \( \eta(t) \).

Eq. (5) is the basic signal model that will be used in the rest of the paper for the development of a space-time technique suitable for unambiguous BOC tracking. When BOC signals are considered, algorithms should be developed to reduce the impact of \( \eta_{m,h} \) that include receiver noise, interference and multipath components, along with the mitigation of ambiguities in \( R(\Delta \tau_h) \).

Space-time processing techniques (Kohno 1998) have the potential to fulfill those requirements. A brief introduction to space-time processing and existing methodologies in the field of GNSS is provided in the next section.

3 SPACE-TIME PROCESSING

A simplified representation of a typical space-time processing structure is provided in Figure 1. Each antenna element is followed by \( K \) taps with \( \delta \) denoting the time delay between successive taps forming the temporal filter. The combination of several antennas forms the spatial filter. \( w_{mk} \) are the space-time weights with \( 0 \leq k < K \) and \( 0 \leq m < M \). \( k \) is the temporal index and \( m \) is the antenna index.

The array output after applying the space-time filter can be expressed as

\[ z(t) = \sum_{n=0}^{M-1} \sum_{k=0}^{K-1} (w_{nk}^\ast \tilde{y}_n(t - k\tau)) \]  

(7)

where \( (\cdot)^\ast \) denotes complex conjugate. The spatial-only filter can be realized by setting \( K = 1 \) and a temporal only filter is obtained when \( M = 1 \). The weights are updated depending on the signal/channel characteristics subject to user-defined constraints using different adaptive techniques (Haykin 2001). This kind of processing is often referred to as Space-Time Adaptive Processing (STAP). The success of STAP techniques has been well demonstrated in radar, airborne and mobile communication systems (Klemm 2006, Ward 1998). This has led to the application of STAP techniques in the field of GNSS signal processing. Several STAP techniques (O’Brien & Gupta 2008, Vicario et al. 2010, Seco-Granados et al. 2005, Rougerie et al. 2011) have been developed for improving the performance of GNSS signal processing. These techniques exploit the advantages of...
STAP to minimize the effect of multipath and interference along with improving the overall signal quality.

Space-time processing algorithms can be broadly classified into two categories: decoupled and joint space-time processing (Paulraj & Lindskog 1998). The joint space-time approach exploits both spatial and temporal characteristics of the incoming signal in a single space-time filter while the decoupled approach involves several temporal equalizers and a spatial beamformer that are realized in two separate stages as shown in Figure 2.

When considering the decoupled approach for GNSS signals, temporal filters can be applied on the data from the different antennas whereas the spatial filter can be applied at two different stages, namely pre-correlation or post-correlation. In the pre-correlation stage, spatial weights are applied on the incoming signal after carrier wipe-off while in the post-correlation stage, spatial weights are applied after the Integrate & Dump (I&D) block on the correlator outputs defined by (5). In pre-correlation processing, the update rate of the weight vector is in the order of MHz (same as the sampling frequency) whereas the post-correlation processing has the advantage of lower update rates in the order of kHz (I&D frequency). In the pre-correlation case, the interference and noise components prevail significantly in the spatial correlation matrix and would result in efficient interference mitigation and noise reduction. But the information on direct and reflected signals are unavailable since the GNSS signals are well below the noise level. This information can be extracted using post-correlation processing.

In (O’Brien & Gupta 2008), joint STAP has been considered. The weights are adapted in order to minimize the MSE between the incident signal and a reference signal. Linear constraints are included to guarantee zero carrier phase and code delay biases. In this kind of processing, the knowledge of the input signal power spectrum, the response of the front-ends and the antenna response of each element in the array are required. A hybrid beamformer made of a weighted combination of the minimum MSE and the minimum-variance beamformer was considered in (Seco-Granados et al. 2005). The main objective of the hybrid beamformer was to cancel multipath components as well as interference to take complete advantage of the spatial dimension. Hence post-correlation processing was adopted. In (Vicario et al. 2010) and (Rougerie et al. 2011), adaptive spatial processing was considered based on constrained minimum variance distortionless response (MVDR) beamformer and the space alternating generalized expectation-maximization (SAGE) algorithms. In both cases, post correlation processing was employed.

Recently, space-time algorithms applicable to Galileo signals have been considered in (Cuntz et al. 2008, Iubatti et al. 2006). Live Galileo data were used in (Cuntz et al. 2008) to demonstrate the operation of a Galileo navigation receiver using antenna arrays. A linearly constraint minimum variance beamformer was used to steer the array beam to the incoming Galileo signal Direction of Arrival (DoA). Improvements due to the antenna array were provided with respect to the single antenna processing in terms of C/N0 estimates. An interference mitigation technique for Galileo E1 frequencies was proposed in (Iubatti et al. 2006) that jointly exploits the advantages of space-time-frequency domains. In order to achieve interference mitigation, a projection based algorithm to remove undesired interference signals was proposed. Here the incoming signal was projected on to the interference orthogonal subspace and later a joint space-time filter was applied. In all the mentioned papers, the problem of ambiguous BOC tracking was not considered.

In this research work, the decoupled space-time processing structure has been considered. Temporal processing is applied at each antenna output and spatial processing is applied at the post-correlation stage. Temporal processing based on MMSE equalization and spatial processing based on the adaptive MVDR beamformer are considered.

### 4 PROPOSED METHODOLOGY

The proposed STAP architecture for BOC signal tracking is provided in Figure 3.
In this approach, the incoming BOC signals are at first processed using a temporal equalizer (Anantharamu 2011) that produces a signal with a BPSK-like spectrum. The filtered spectra from several antennas are then combined using a spatial beamformer that produces maximum gain at the desired signal direction of arrival. The beamformed signal is then fed to the code and carrier lock loops for further processing. The transfer function of the temporal filter is obtained by minimizing the error (Anantharamu et al. 2011b):

$$
E_{MMSES} = \int_{-\Delta f}^{\Delta f} \left[ G_{d}(f) - G_{i}(f) H(f) \right]^2 \, df + \frac{\lambda N_0}{C} G_{i}(f) |H(f)|^2 \, df
$$

where $H(f)$ is the transfer function of the temporal filter that minimizes the MSE, $E_{MMSES}$, between the desired spectrum, $G_{d}(f)$, and filtered spectrum, $G_{i}(f) H(f)$. The spectrum of the incoming BOC signal is denoted by $G_{i}(f)$, $\lambda$ is a weighting factor determining impact of noise with respect to that of an ambiguous correlation function. $N_0$ is the noise power spectral density and $C$ the carrier power.

The solution of (8) is given by (Anantharamu et al. 2011b):

$$
H(f) = \frac{G_{d}(f)}{G_{i}(f) + \frac{\lambda N_0}{C}}.
$$

A sample plot of the ACF obtained after applying MMSES on live Galileo BOCs(1,1) signals collected from the GIOVE-B satellite is shown in Figure 4. The input C/N$_0$ was equal to 40 dB-Hz and the ACF was averaged over 1 s of data. It can be observed that the multi-peaked ACF was successfully modified by MMSES to produce a BPSK-like ACF without secondary peaks. Also narrow ACF were obtained by modifying the filter design for improved multipath mitigation. Thus using temporal processing, the antenna array data are devoid of ambiguity caused due to the presence of the sub-carrier.

After temporal equalization, the spatial weights are computed and updated based on the following information:

a. The signal and noise covariance matrix obtained from the correlator outputs;

b. Calibration parameters estimated according to the algorithm described in (Anantharamu et al. 2011a) to minimize the effect of mutual coupling and antenna gain/phase mismatch;

c. Satellite data decoded from the ephemeris/almanac containing information on the GNSS signal DoA.
The weights are updated using the iterative approach (Du et al. 2009) for the MVDR beamformer to maximize the signal quality according to the following steps:

**Step 1:** Update the estimate of the steering vector for the $h^{th}$ satellite using the calibration parameters as

$$\hat{q}_{m,h} = q_{m,h} \sum_{j=1}^{M-1} \left( \bar{v}_{m,j} \bar{s}_{h}^{w} \right)^{T}$$

Here $\bar{v}_{i,j}$ represents the estimated calibration parameters using the correlator outputs given by (5) (Anantharamu et al. 2011a) and $s_{h}^{w}$ is the element of the steering vector computed using the satellite ephemeris/almanac data.

**Step 2:** Update the weight vector $w_{h} = [w_{h}^{0}, w_{h}^{1}, \ldots, w_{h}^{M-1}]$ (the temporal index, $k$, is removed for ease of notation) using the new estimate of the covariance matrix and steering vector as

$$\hat{R}_{m} = \frac{1}{T} \left( \tilde{y}^{Caw}(t) \right) \left( \tilde{y}^{Caw}(t) \right)^{H}$$

$$w_{h} = \frac{\hat{R}_{m} \hat{s}_{h}}{s_{h}^{H} \hat{R}_{m-1} \hat{s}_{h}}$$

where $\tilde{y}^{Caw}(t)$ is the input signal $\tilde{y}(t)$ after carrier wipe-off as

$$\hat{y}^{Caw}(t) = \hat{y}_{m}(t) \exp \{ -j\theta_{s} \}$$

Repeat Steps 1 and 2 until the weights converge. Finally compute the correlator output to drive the code and carrier tracking loop as

$$z = \hat{q}_{h} w_{h}^{H}$$

where $\hat{q}_{h} = [\hat{q}_{h,0}, \hat{q}_{h,1}, \ldots, \hat{q}_{h,M-1}]$ represents the vector of calibrated post correlator outputs for the $h^{th}$ satellite.

The $C/N_{0}$ gain obtained after performing calibration and beamforming on a two-antenna linear array and four-antenna planar array data collected using the four channel front-end (Morrison 2010) is provided in Figure 5 and Figure 6. The $C/N_{0}$ plots are characterized by the following three regions:

- **Single Antenna** that provides $C/N_{0}$ estimates obtained using $q_{0,h}$ alone,
- **Before Calibration** that provides $C/N_{0}$ estimates obtained by compensating only the effects of the steering vector, $s_{h}$, before combining the correlator outputs from all antennas and
- **After Calibration** that provides $C/N_{0}$ estimates obtained by compensating the effects of both steering vector, $s_{h}$, and calibration matrix, $C_{h}$, before combining correlator outputs from all antennas.

Detailed description of the calibration processing is provided in (Anantharamu 2011). It can be observed that after calibration, beamforming provides approximately a $C/N_{0}$ gain equal to the theoretical gain on most of the satellites whereas before calibration, the gain is minimal and, in some cases, negative with respect to the single antenna case. These results support the effectiveness of the adopted calibration algorithm and the proposed methodology that enables efficient beamforming.

### 5 RESULTS AND ANALYSIS

In this section, results obtained using simulated data and live GNSS signals are provided.

#### 5.1 Simulation analysis

IF simulated BOCs(1,1) signals for a 4-element planar array with array spacing equal to half the wavelength of
the incoming signal has been considered to analyze the proposed algorithm. The input signal was characterized by a C/N\_0 equal to 42 dB-Hz at an angle of arrival of 20° elevation and 315° azimuth angle.

A sample plot of the antenna array pattern using the spatial beamformer (11) is shown in Figure 7. In the upper part of Figure 7, the ideal case in the absence of interference was considered. The algorithm is able to place a maximum of the array factor in correspondence of the signal DoA.

Figure 7 Antenna array pattern for a 4-element planar array computed using a MVDR beamformer in the presence of two interference sources

In the bottom part, results in the presence of interference are shown. Two interference signals were introduced at 60 and 45 degree elevation angles. It can be clearly observed that, in the presence of interference, the MVDR beamformer successfully adapted the array beam pattern to place nulls in the interference DoA.

In order to further test the tracking capabilities of the full system, semi-analytic simulations were performed using an extended version of the model proposed by (Borio et al. 2010) for the analysis of digital tracking loops. The simulation scheme is shown in Figure 8 and consists of \( M \) antenna elements. Each antenna input for any \( h \)th satellite is defined by a code delay \( \tau_{m,h} \) and a carrier phase value \( \phi_{m,h} \) for DLL and PLL analysis. \( \phi_{m,h} \) captures the effect of mutual coupling, antenna phase mismatch and phase effects due to different antenna hardware paths. To analyze the post-correlation processing structure, each antenna input is processed independently to obtain the error signal, \( \Delta \tau_{m,h}/\Delta \phi_{m,h} \) as

\[
\Delta \tau_{m,h}/\Delta \phi_{m,h} = \tau_{m,h}/\phi_{m,h} - \hat{\tau}_h/\hat{\phi}_h,
\]

where \( \hat{\tau}_h/\hat{\phi}_h \) are the current delay/phase estimates.

Figure 8 Semi-analytic simulation model for a multi-antenna system comprising \( M \) antennas with a spatial beamformer

Each error signal is then used to obtain the signal components that are added along with the independent noise components, \( \tilde{r}^m, \tilde{r}_c^m, \tilde{r}_d^m \). The combined signal and noise components from all antenna elements are fed to the spatial beamformer to produce a single output according to the algorithm described in Section 4. Finally, the beamformer output is passed through the loop discriminator, filter and NCO to provide a new estimate \( \hat{\tau}_h/\hat{\phi}_h \). The Error to Signal mapping block and the noise generation process accounts for the impact of temporal filtering.

Sample tracking jitter plots for a PLL with a single, dual and three-antenna array system obtained using the structure described above are provided in Figure 9.

Figure 9 Phase tracking jitter obtained for single, dual and three antenna linear array as a function of the input C/N\_0 for a Costas discriminator (20 ms coherent integration and 5 Hz bandwidth)
The number of simulation runs considered was 50000 with a coherent integration time of 20 ms and a PLL bandwidth equal to 5 Hz. As expected the tracking jitter improves when the number of antenna elements is increased along with improved tracking sensitivity. As expected, the C/N\textsubscript{0} values at which loss of lock occurs for a three antenna system is reduced with respect to the single antenna system, showing its superiority.

5.2 Real data analysis

The experimental setup considered for the analysis of the proposed combined space-time algorithm is shown in Figure 10. Two antennas spaced 8.48 cm apart were used to form a 2-element linear antenna array structure. The NI front-end was employed for the data collection process to synchronously collect data from the two-antenna system.

Figure 10 Experimental setup with signals collected using two antennas spaced 8.48 cm apart

Data on both channels were progressively attenuated by 1 dB every 10 s to simulate a weak signal environment until an attenuation of 20 dB was reached. When this level of attenuation was reached, the data were attenuated by 1 dB every 20 s to allow for longer processing under weak signal conditions. In this way, data on both antennas were attenuated simultaneously. Data from Antenna 1 were passed through a splitter, as shown in Figure 10, before being attenuated in order to collect signals used to produce reference code delay and carrier Doppler frequencies.

BOCs(1,1) signals collected using Figure 10 were tracked using the temporal and spatial processing technique described in Figure 3. The C/N\textsubscript{0} results obtained using single and two antennas are provided in Figure 11. In the single antenna case, only temporal processing was used. In this case, the loop was able to track signals for an approximate C/N\textsubscript{0} of 19 dB-Hz. Using the space-time processing, the dual antenna system was able to track for nearly 40 s longer than the single antenna case, thus providing around 2 dB improvement in tracking sensitivity.

6 CONCLUSIONS

In this paper, a combined space-time technique for the processing of new GNSS signals; a temporal filter at the output of each antenna, a calibration algorithm and a spatial beamformer has been developed. The proposed methodology has been tested with simulations and real data. It was observed that the proposed methodology was able to provide unambiguous tracking after applying the temporal filter and enhance the signal quality after applying a spatial beamformer. The effectiveness of the proposed algorithm to provide maximum signal gain in the presence of several interference sources was shown using simulated data. C/N\textsubscript{0} analysis for real data collected using a dual antenna array showed the effectiveness of combined space-time processing in attenuated signal environments providing around a 2 dB improvement in tracking sensitivity.

REFERENCES


