NOVEL MIMO SAR FOR URBAN REMOTE SENSING APPLICATIONS

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ABSTRACT:

The world is experiencing a rapid rate of urban expansion mainly caused by the rapid population growth. Remote sensing images can give patterns of urban growth, but urban areas are difficult to map because of the wide range of spectral signatures, sometimes combined with the occurrence of mixed pixels. So, some effective new remote sensing means should be developed. Inspired by recent advance in multiple-input and multiple-output (MIMO) radar, this paper investigated the applications of MIMO SAR (synthetic aperture radar) for urban mapping. The fundamental difference between MIMO SAR and other SAR is that the latter seeks to maximize coherent processing gain, while MIMO SAR capitalizes on the diversity of target scattering to improve imaging performance. This paper deals with conceptual analysis, as opposed to technological implementation. The system concept, signal models, and corresponding processing algorithm are formed. Some potential applications are investigated. It is shown that MIMO SAR may provide a satisfied solution to urban remote sensing.

1. INTRODUCTION

The world is experiencing a rapid rate of urban expansion mainly caused by the rapid population growth together with the improved efficiency in the transportation sector and increasing dependence on cars. Consequently, changes in land use and land cover can transform the habitat and microclimatic patterns. Thus, rehabilitating cities, soil and water conservation, participatory planning, individual lifestyle changes, are some of the measures that can be under-taken to minimize urban sprawl. However, the adoption of such new policies requires new strategies supported by new tools. In this case, microwave remote sensing and geographic information systems (GIS) are important tools, because microwave remote sensing images give patterns of urban growth, while GISs record data and its transformed information support decision making.

However, urban areas are difficult to map because of the wide range of spectral signatures, sometimes combined with the occurrence of mixed pixels. Atmospheric effects and temporal gaps between different sensors contribute to inaccuracies in urban mapping. It is concluded in (Paul, 2007) that urban mapping can be improved through: accurate spatial registration, appropriate field verification, improved classification algorithms, and the use of high spatial and spectral resolution satellite imagery. But, even as good as current synthetic aperture radar (SAR) techniques, they cannot effectively handle the imaging problems of target RCS (radar cross section) scintillations, and varying or unstable signatures (Dunn and Howard, 1968). But these targets represent an important kind of SAR applications dealing with urban mapping. Both experimental measurements and theoretical results demonstrate that scintillations of 10—15dB in the reflected energy may be experienced for a small change in aspect angle (Skolnik, 2002). This scintillation will cause degradation in the SAR imagery, even make a reliable target detection impossible.

Inspired by recent advance in multiple-input and multiple-output (MIMO) radar (Fishler et al., 2006, Bekkerman and Tabrikian, 2006), this paper investigated the applications of MIMO SAR for urban mapping. Given that MIMO Radar is in its infancy, there is no one clear definition of what it is. It is generally assumed that independent signals are transmitted through different antennas, and that these signals, after propagating through the environment, are received by multiple antennas (Forsythe and Bliss, 2005). Generally speaking, MIMO radar has two advantages while compared to traditional radars: one is diversity, given differences in viewing angles on a particular target, the diversity in the scattering response of the target can overcome performance degradations caused by RCS scintillations (Lehmann et al., 2006) and significantly improve parameter identifiability (Li et al., 2007). The second advantage is resolution improvement. Due to the significantly larger number of degrees-of-freedom of a MIMO system, improved resolution can be achieved by coherently processing of multiple simultaneous waveforms at multiple receivers.

Literature search shows that current researches are usually focus on transmitter/receiver design, signal detection and estimation, and waveform design (Yang and Blum, 2007), but little work on the MIMO radar with moving platforms has been reported. Even less effort has been placed on MIMO SAR (Wang, 2007). We have investigated the system concept of MIMO SAR and its advantages over general SAR in (Wang, 2007). The key aspect of a MIMO SAR is the use of M orthogonal waveforms each transmitted from different phase centers and N received phase centers. At each of the receive phase centers, the received signals are matched filtered for each of the transmitted waveforms forming $M \times N$ channels. This differs substantially from current SAR in which closely spaced antenna arrays are used. With closely spaced antenna elements, it is possible to cohere a beam toward a direction in space and to realize a coherent processing gain. However, general SAR is prone to severe target fading, and hence it may suffer considerable performance degradation. In contrast, MIMO SAR cannot cohere a beam toward a certain direction in space. But, MIMO SAR can exploit target angular spread to combat target fading because it consists of many independent SARs, each of them sees a different aspect of the target, enabling the MIMO SAR to exploit spatial diversity to overcome target fading.

This paper investigates the applications of MIMO for urban remote sensing. The emphasis is placed on presenting system concept, signal model, and its potential applications. The remaining sections of this paper are organized as follows. Section 2 develops a system model of MIMO SAR. Next, Section 3 designs an example MIMO SAR waveform, while Section 4 investigates its potential applications in urban remote sensing. This paper concludes in Section 5 with some summary and concluding remarks.

2. SYSTEM MODEL

It is well known that, general SAR achieves its high spatial resolution in range direction by utilizing wideband transmitted pulses, and high resolution in azimuth direction by exploiting the relative motion between target and radar platform, which leads to target returns having a Doppler bandwidth. In a MIMO SAR, the space between the array elements is large, and each element observes a different aspect of the target. Thus, the point source model is not adequate to describe the received signal in MIMO SAR. Hence the classic Swerling-I model should be extended to MIMO systems.

As shown in Fig. 1, suppose a MIMO SAR system that utilizes an array with M antennas at the transmitter, and N antennas at the receiver. Note that the transmitter and receiver are not necessarily collocated (i.e. bistatic SAR). Suppose also that a far field complex target that consists of Q independent scatterers with approximately the same RCS, i.e., a target composed of many small reflectors. The target is illuminated by narrowband signals whose amplitude does not change appreciably across the target. Each scatterer is assumed to have isotropic reflectivity modeled by zero-mean, unit-variance per dimension, independent and identically distributed complex random variables ς_q . The target is then modeled by $\sum$ = $(1/\sqrt{2Q})diag(\varsigma_0,\varsigma_1,\varsigma_2,.......\varsigma_{Q-1})$, where the normalization factor makes the target RCS $E\left[Tr\left(\sum\sum^*\right)\right]=1$ independent of the number of scatterers in the model. This assumption corresponds to the RCS fluctuations are fixed during an antenna scan, but vary independently scan to scan (in azimuth).

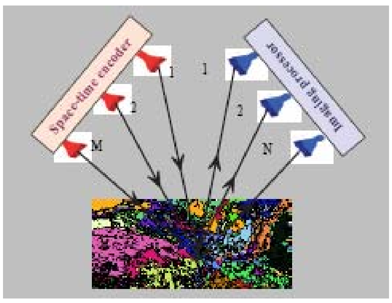

Figure 1. System model of MIMO SAR system.

We assume that the antennas at the two ends of the system are sufficiently spaced such that a possible target or clutter provide uncorrelated reflection coefficients between each transmit/ receive pair of sensors. The baseband transmitted signal for temporal block i and transmit antenna m is given by

$$s_{m.i}(t)=\sum_{k=1}^{K}x_{m,k}(i)\,p\left[t-(k-1)T\right],m=1,2,.....M. \tag{1}$$

where K is the number of pulses in each temporal block, t is the fast-time (reinitialized each pulse), T is the pulse duration and $p(t)$ is the baseband pulse shaping function for antenna m, which we assumed, without loss of generality, with unit energy and duration τ_p . Here $x_{m,k}(i)$ is the transmitted space-time code for block i , given by

$$x_{m,n}(i)=w_m(i)\cdot a_{m,n}(i). \tag{2}$$

where $a_{m,n}(i)$ is an *unitary* code and $w_m(i)$ denotes the transmitter beamformer weights for block i . The signals are modulated onto a carrier with frequency f_0 (Hz). Suppose a single target located at a radial distance r with respect to the origin located at a reference element of the transmit array. In the case where there is a constant distance between the arrays, the two-way delay and Doppler from element m to element n are (White and Ray, 2006)

$$\tau_{m,n}(i)=\frac{2r(i)-(n+m)d\rho(i)}{c} \tag{3}$$

$$v_{m,n}(i)=\frac{\left[2\dot{r}-(n+m)d\,\dot{\rho}(i)\right]f_0}{c} \tag{4}$$

where d is the array spacing, ρ is the target wavenumber, with $\dot{\rho}$ being its time derivative, and $\dot{r}$ is the target velocity.

The baseband received signal at an antenna m for transmit block i is

$$r_{n,i}(t,\tau)=a(i)e^{j\phi(i)}\sum_{m=1}^{M}s_{m,i}\left[t-\tau_{m,n}(i),\tau\right] \times e^{2\pi jtv_{m,n}(i)}e^{-j2\pi f_0\tau_{m,n}(i)}+\zeta_{m,n}(t,\tau) \tag{5}$$

where τ is the slow-time in azimuth, $a(i)\geq 0$ is the target reflectivity amplitude, and $\phi(i)$ denotes the associated phase shift. The quantities $\zeta_{m,n}(t,\tau)$ represent receiver noise, and are assumed to be zero-mean spatially uncorrelated, complex Gaussian noise. The baseband signal, at each of the receiver elements, is matched filtered with the transmitted waveforms.

The filter output is expressed as

$$y_n(t,\tau)=a(i)e^{j\phi(i)}\sum_{m=1}^{M}\left\{s_{m,i}\left[t-\tau_{m,n}(i),\tau\right]\otimes s_{m,i}(t)\right\} \times e^{2\pi jtv_{m,n}(i)}e^{-j2\pi f_0\tau_{m,n}(i)}+N_n(t,\tau) \quad (6)$$

where $\otimes$ is the convolution, and $N_n(t,\tau)$ is the delay-dependent channel estimation noise, produced by filtering the time-dependent noise vector.

MIMO SAR generates $M\times N$ channels. Each of these channels has an associated two-way phase centre. To reconstruct a single spatial sample it is necessary to combine different channels. The MIMO SAR concept ensures that this is possible and all the MIMO channels are used once and once only, thus providing the full range resolution potential. After all the spectrum components are extracted, they are then rearranged to achieve the unambiguous full spectrum. Then the unambiguous full-spectrum signal can be processed by using conventional SAR image formation algorithms.

3. EXAMPLE WAVEFORM

In a MIMO SAR, each antenna of the array transmits a unique waveform, orthogonal to waveforms transmitted by the other antennas. Yang *et. al* (Yang and Blum, 2006) have considered waveform design for MIMO radar mainly for estimation of extended targets. They presented a quantitative analysis demonstrating the relationship between the information theoretic and estimation theoretic criteria. Practically, low cross-correlation between waveforms avoids interference and hence results independent information gains from target signature at various angles. Similarly, low aperiodic autocorrelation peak sidelobe ratio ensures high range resolution, high signal-to-noise ratio (SNR) and high resolution of multiple targets. Thus, the waveforms with low aperiodic cross-correlation and auto-correlation peak sidelobe ratio and tolerance to small Doppler shifts are desired for MIMO SAR systems. So far, research into MIMO radar/SAR waveform diversity has mainly been for proof-of-concept. In this paper, three typical chirps, as shown in Fig. 2, are investigated. A quantity of interest is the relative level between the correlation of identical (wanted) chirp waveforms to the correlation of different (unwanted) chirps waveforms.

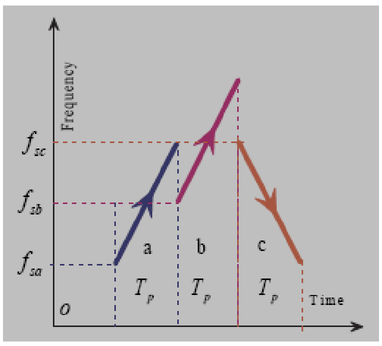

Figure 2. Example chirp waveforms using for MIMO SAR.

Since a chirp waveform can be represented by the start frequency f_s, the chirp rate $k=B/T_p$, and the chirp duration T_p, we have

$$s(t)=rect\left(\frac{t}{T_p}\right)\exp\left\{j\pi\left[2f_st+kt^2\right]\right\} \quad (7)$$

with *rect* a window function. The possibilities of processing multiple chirps waveforms can be investigated by analyzing the correlation performance. The correlation function between two signals $x(t)$ and $y(t)$ is defined as (Manolakis et al., 2000)

$$R_{xy}(\tau)=\int_{-\infty}^{+\infty}x^*(t)y(t+\tau)dt \quad (8)$$

From Eq. (7) we have (where the subscripts i and j relate the quantities to one of two chirps.)

$$\begin{aligned}R_{s_is_j}(\tau)&=\int_{-\infty}^{+\infty}s_i^*(i)s_j(t+\tau)dt\\&=\int_{t_i}^{t_j}\exp[j\pi(-2f_{si}t-k_it^2+2f_{sj}t\\&+2f_{sj}\tau+k_jt^2+k_j\tau^2+k_jt\tau)]dt\\&=\int_{t_i}^{t_j}\exp\left[j\frac{\pi}{\sqrt{2}}\left(\frac{f_{sj}+k_j\tau-f_{si}}{\sqrt{k_j-k_i}}+\sqrt{2(k_j-k_i)}t\right)^2\right]dt\\&\times\exp\left[j2\pi f_{sj}+j\pi k_j\tau^2-j\pi\frac{(f_{sj}+k_j\tau-f_{si})^2}{k_j-k_i}\right]\end{aligned} \quad (9)$$

where t_i and t_j denote the integration limits. Let

$$\gamma(t)=\frac{f_{sj}+k_j\tau-f_{si}}{\sqrt{k_j-k_i}}+\sqrt{2(k_j-k_i)}t \quad (10)$$

we have

$$d\gamma=\sqrt{2(k_j-k_i)}dt \quad (11)$$

Hence Eq. (9) can be further simplified into

$$R_{s_is_j}(\tau)=\frac{\exp\left[j2\pi f_{sj}+j\pi k_j\tau^2-j\pi\frac{\left(f_{sj}+k_j\tau-f_{si}\right)^2}{k_j-k_i}\right]}{\sqrt{2(k_j-k_i)}}\times\int_{\gamma(t_i)}^{\gamma(t_j)}\exp\left(j\frac{\sqrt{2}\pi}{2}\gamma^2\right)d\gamma \quad (12)$$

where

$$\begin{aligned}\int_{\gamma(t_i)}^{\gamma(t_j)} \exp\left(j\frac{\sqrt{2}\pi}{2}\gamma^2\right)d\gamma &= \int_0^{\gamma(t_j)} \exp\left(j\frac{\sqrt{2}\pi}{2}\gamma^2\right)d\gamma \\ &\quad -\int_0^{\gamma(t_i)} \exp\left(j\frac{\sqrt{2}\pi}{2}\gamma^2\right)d\gamma \\ &= C\left(\gamma\left(t_j\right)\right) + jS\left(\gamma\left(t_j\right)\right) \\ &\quad -C\left(\gamma\left(t_i\right)\right) - jS\left(\gamma\left(t_i\right)\right)\end{aligned} \tag{13}$$

To be more practical, the chirps with equal duration ($T_{pi} = T_{pj}$) and equal absolute value of chirp rate ($|k_i = k_j|$) are preferred. As an example, assuming the following parameters $k_a = k_b = k_c = k = 2 \cdot 10^{12}\, Hz/s$, $B_a = B_b = B_c = B = 2GHz$, $f_{sa} = -1GHz$, $f_{sb} = 0GHz$ and $f_{sc} = 1GHz$, their correlation results are shown in Fig. 3. We can notice that R_{ab} achieves a higher suppression than R_{ac} . Further simulation shows that using an adjacent frequency band for the inverse chirps offers an additional suppression of the cross-correlation component. However, using an adjacent frequency band will result in wider total bandwidth and complexity for radar hardware system. To overcome this disadvantage, the waveforms with the start frequency relation $f_{sj} - f_{si} = B$ and inverse chirp rate $|k_i = k_j|$ can be used.

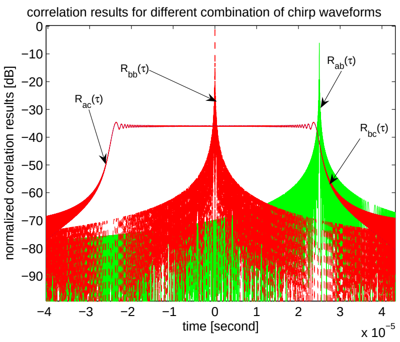

Figure 3. Correlation results for different combinations.

4. POTENTIAL APPLICATIONS

Timely and accurate change detection of urban areas is important for developing strategies for minimizing urban poverty and the related environmental effects. Updating urban and natural resources maps will continue to be a critical factor in sustainable development. Remote sensing techniques have been investigated for human settlement detection, population estimation, and urban analysis since the mid-1950's. But, a literature search indicates that urban studies based on radar imagery have received much less attention than studies of vegetation, soils, geology, geomorphology, and related parameters of the physical landscape. Radarsat International compiled a bibliography of applied SAR research in the geosciences between 1987 and 1992. Of 285 articles only 16 were categorized under "urban mapping". One reason contributing to this lack of attention is the high variability of the urban landscape and the complexities of the interactions between the radar signal and the human built-up environment. With the arrival of operational MIMO SAR, effective urban remote sensing may be possible.

MIMO SAR remote sensing can provide urban planners with crucial data necessary for urban analysis such as: 1) spatial extent and location of urban areas; 2) land use change detection; 3) census rated statistics; 4) spatial distribution of the different land use and land cover types; 5) land use impact analysis; 6) transportation networks and related infrastructure; and 5) improved performance in spatial, spectral and radiometric resolution. All in all, possible applications of MIMO SAR may be: 1) mapping urban land use patterns and change; 2) human settlement detection; 3) population estimation; 4) interpretation of urban socioeconomic conditions; 5) assessment of human activities on the physical landscape.

5. CONCLUSIONS

Urban areas occupy a relatively small part of the world's surface, but a very important segment in terms of the world's population, actual and potential impact on the environment and ecosystem, land values, migration patterns, and economic importance. Methods to improve the efficiency and accuracy of data collection and analysis are needed and continually being sought. Remote sensing is one such technique being explored to answer these needs. However, general SAR suffers from the problem almost all remote sensing systems do in defining land cover/land use categories, namely, that spectral classes that can be defined from the imagery do not always coincide with the information classes sought by the user community. To overcome these disadvantages, the use of MIMO SAR for urban remote sensing was proposed in this paper. The application of MIMO SAR can greatly improve detection and estimation performance because of the reduction in target fades, and offer a number of potential advantages, including improved resolution and sensitivity. Specifically, MIMO SAR overcomes target RCS fluctuation by averaging over many decorrelated channels. Subsequently, the received signal is a superposition of independency faded signals, and the average SNR of the received signal is more or less constant. Moreover, the spatial diversity of MIMO radar also eliminates the deep interference nulls in the elevation coverage because of surface multipath reflection (Fishler et al., 2004). Thus, it appears that MIMO SAR can provide a promising solution to urban remote sensing. Although exploring the potential of MIMO SAR will take significant work on many fronts, we are indeed convinced the effort will be worth it.

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