

Synchronisation of Bistatic Radar Systems

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Abstract—Bistatic radar is gaining more and more interest over the last years. It offers more freedom to deploy the transmitter and the receiver, e. g. in a way to enhance the signature of stealthy targets. Furthermore the bi- or multistatic system can be realized without using expensive transmit/receive-modules. An additional feature of bistatic radar is that continuous wave signals can be used. A crucial problem associated with bi- and multistatic systems is the synchronisation of time and frequency at the transmitters and receivers for coherent signal processing and range measurement. Modern communications satellites and world wide accessible GPS signals allow to synchronise the time easily over a long period with a time difference of less than 1 ns. The required frequency stability depends on the baseline and may vary with application. Image generation with bistatic SAR systems requires a frequency coherence for at least the coherent integration time. For interferometric SAR systems this coherence has to be expanded over the whole processing time. The paper will concentrate on the problem of time and frequency synchronisation between a bistatic transmitter and receiver pair. Possible solutions for attaining the requirements of bistatic radar systems will be discussed.

I. INTRODUCTION

Bistatic radar has been gaining more and more interest over the years as it offer various advantages. For instance, the transmitter and receiver can be realized without expensive transmit/receive modules. Furthermore, separating transmitter and receiver open ups new possibilities. For instance, deploying the transmitter further away from the scene, or even using multiple expendable transmitters on UAVs, can reduce the vulnerability. Beyond this, with large baselines it is likely to increase the signature from stealthy objects. Another interesting aspect of bistatic imaging radar is the reduced dynamic range of difficult imaging environments such as urban ones.

In recent years the requirements imposed on bistatic radar systems have increased steadily. Directly associated with these requirements, one has to solve the problem of highly accurate time and frequency synchronization for coherent signal processing. If moving platforms are involved, as in the case of synthetic aperture radar (SAR), high precision navigation is an issue for motion compensation. Phase noise is also an issue for bistatic radars, as it limits the coherent signal processing.

For ground based bi-/multistatic radar with moderate bandwidth, time and frequency synchronization can be easily obtained using the global positioning system (GPS), which provides a highly stable pulse-per-second signal (PPS). Independent GPS disciplined low phase-noise crystal oscillators are used to maintain site-pair coherence. The standard deviation of the PPS signal between two low-cost commercial GPS

units seeing the same satellites can be as low as 15 ns. Using this PPS signal to synchronize a highly stable quartz crystal oscillator, one can expect a standard deviation of less than 5 ns. Frequency synchronization is realized by generating all needed frequencies by dividing, multiplying or phase-locking to the GPS disciplined oscillators at the transmitter and receiver site.

II. TIME SYNCHRONISATION

Time synchronisation between the separated transmitter and receiver of a bistatic radar is required for range measurement. The time accuracy is on the order of a fraction of that of the frequency. A typical requirement for time synchronisation is about the tenth of the transmitted compressed pulse width.

$$\delta t = \frac{\tau}{20 \tau_{\square}} = \frac{1}{20 B \tau_{\square}} \quad (1)$$

with δt the time difference, τ the pulse width, B the frequency bandwidth and $\tau_{\square}$ the update rate of the clocks. For example,

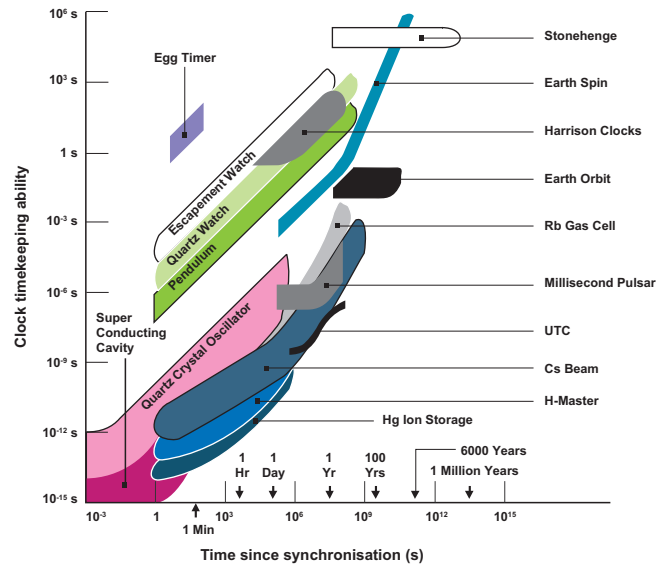


Fig. 1. Clock timekeeping ability over synchronisation [1]

when a bistatic system uses a bandwidth of $B = 360$ MHz and the update rate of the clock is $\tau_{\square} = 30$ seconds, the time stability has to be $\delta t = 4 \cdot 10^{-12}$ s. From Fig. 1 it can be seen that this can be achieved using high quality crystal oscillators (BVA). Beside a very good timekeeping ability these oscillators show a very low phase noise. A synchronisation signal for timing can be exchanged through optical fiber

(typical time transfer accuracy capability: $\delta t = 0.1 \dots 0.5$ ns) or coaxial cable ($\delta t = 1 \dots 10$ ns) if the stations are not far apart. If there exists a line-of-sight the synchronisation can be achieved by direct signal ($\delta t = 1 \dots 10$ ns). Today, it is also possible to attain coherence by using navigation satellites (e.g. Global Positioning System), which provide a highly stable pulse-per-second signal. In case the receivers are using the same satellites for timing (common view) a time accuracy of $\delta t = 5 \dots 20$ ns can be achieved [2].

Another common way of time synchronisation between two locations is to set up a two-way communication link. This can be a direct microwave link or a link via a communications satellite (see Fig. 2) [3]. The satellite link features a reduced interference with the surrounding environment in contrast to the direct link. For the two-way time synchronisation the measurement consists of a simultaneous time interval measurement at both sides. The local PPS starts both the local time interval counter and, transmitted via the direct microwave link or via satellite, stops the remote time interval counter. The time difference is roughly $T_1 - T_2 \sim \frac{1}{2}(\Delta T_1 - \Delta T_2)$, where ΔT_i denotes the measured time difference between the local and received PPS at the station i . The time difference has to be exchanged in order to compute the clock difference. This method leads to a standard deviation of approximately 1 ns to 10 ns [3]. A deep knowledge of the satellite motion is not needed for this method as the signal is transmitted in a few milliseconds. The disadvantage of this method is the cost of the equipment.

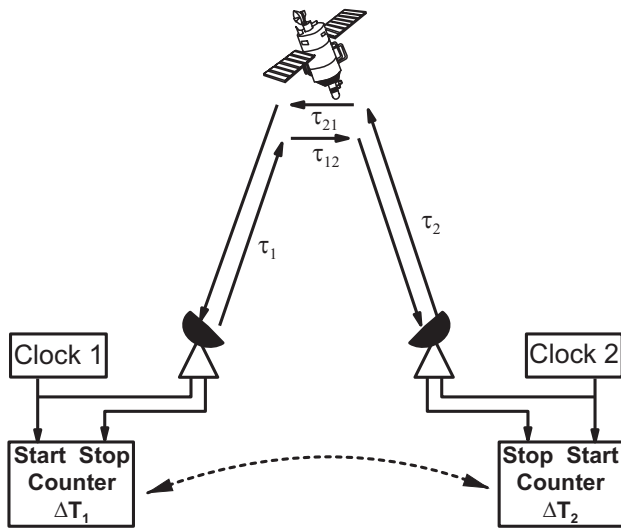


Fig. 2. Time synchronisation over communications satellite

Using the very long baseline interferometry (VLBI) technique developed by the Jet Propulsion Laboratory [4], for baselines up to 800 km one can expect even subnanosecond accuracy at a lower cost than that of the two-way link over a communications satellite. With the VLBI common-view method, where both GPS modules receive the signal from the

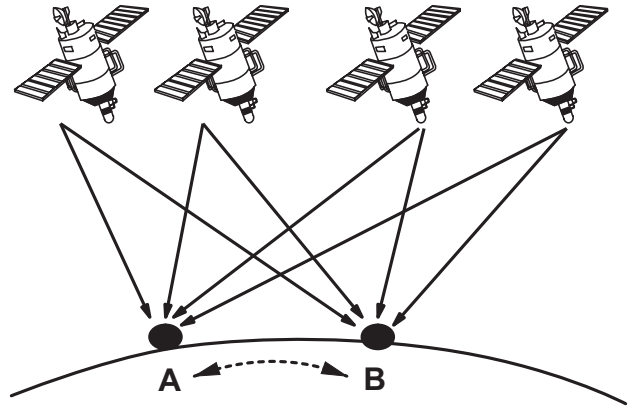


Fig. 3. Time synchronisation using VLBI technique and GPS satellites

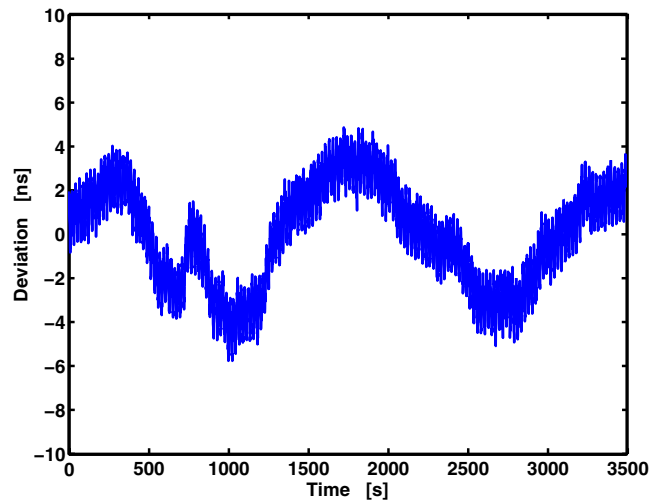


Fig. 4. Deviation between the pulse-per-second from two low-cost timing GPS-units

same satellites at the same time, the ultimate accuracy is about 1 ns. A simple error budget for a baseline of 1000 km shows that one can expect a standard deviation of 8 ns. For time accuracy of this order the coordinates of the receiver must be known with an accuracy less than 30 cm.

Employing off-the-shelf low-cost low-power commercial GPS units, which are using only the L1-signal at 1575.42 MHz, a standard deviation of 15 ns can be achieved between both PPS signals. Disciplining stable local oscillators (STALO) with these PPS signals yields a standard deviation of less than 3 ns, as shown in Fig. 4.

The synchronisation problem is more difficult for airborne platforms. Due to the different motions of the platforms, the coded synchronization signal has to be in the order of several μs to ensure that the motion does not degrade the performance. In addition the synchronisation interval has to be short and the time difference $T_1 - T_2$ has to be exchanged in the

same way between the platforms to obtain synchronised clocks. For calculating the time difference between the platforms the motion has to be taken into account.

Furthermore the coordinates of the transmitter platform has to be passed to the receiver platforms for a dynamical adjustment of the receiving time slot to avoid the loss of receiving pulses.

III. FREQUENCY AND PHASE STABILITY

As with monostatic radars, pulse compression, doppler, or MTI processing is an issue for bistatic radar when phase coherence, phase synchronisation can be established between clocks, or local oscillators, in the transmitter and receiver.

In previous bistatic experiments the phase coherence was obtained by methods similar to those used for time synchronisation. The most promising method was the indirect method by using matched STALOs in the transmitter and receiver, which are again synchronised periodically, for instance to the GPS clock, to remove any long-term frequency drift. Phase accuracy can range from less than one degree to many tens of degrees of RF phase over the coherent processing interval, depending on the type of coherent processing [5].

A. Accuracy requirement

For indirect phase synchronisation using identical STALOs in the transmitter and receiver, phase stability is required over the coherent integration time T_{int} . Thus, the oscillator stability is given by $\Delta\Phi/2\pi f T_{int}$. In the bistatic case, processing is now sensitive to lower frequency or *quadratic* phase errors over T_{int} , and $\Delta\Phi$ can be relaxed to 90° [6]. Thus, for $T_{int} = 10$ s and $f = 10$ GHz, the required stability is $2.5 \cdot 10^{-12}$, which can be fulfilled by a temperature controlled quartz oscillator.

An even higher demand for phase stability exists for interferometric SAR. The requirements depend on the baseline and the desired interferometric quality. A typical demand for the maximum phase error is 3.6° over the typical recording time of 30 seconds, which is used by the PAMIR system. This leads to a frequency accuracy of

$$|f_1 - f_2| < 333.3 \cdot 10^{-6} \text{ Hz} \quad , \quad (2)$$

which is only achievable with ultra high quality oscillators, for instance from PSI. They obtain a stability of $3 \cdot 10^{-11}$ for 1 s for a free running 10 GHz oscillator [7]. Using a 10 MHz BVA-cut oven-stabilised high quality crystal oscillator (OCXO) to discipline this oscillator an aging per day of approx. 10^{-9} Hz can be reached.

To reduce the cost of such a high quality setup two-way phase synchronisation signals, which are derived from the stable local oscillators, are established between both platforms.

Beside the ultra stable oscillators a major concern for interferometric SAR is the very precise knowledge of the baseline between transmitter and receiver. To yield a phase uncertainty of 3.6° the distance between the two receivers must be measured with an accuracy of 0.3 mm if the center frequency of the SAR system is 10 GHz. This is associated with a timing error of 1 ps.

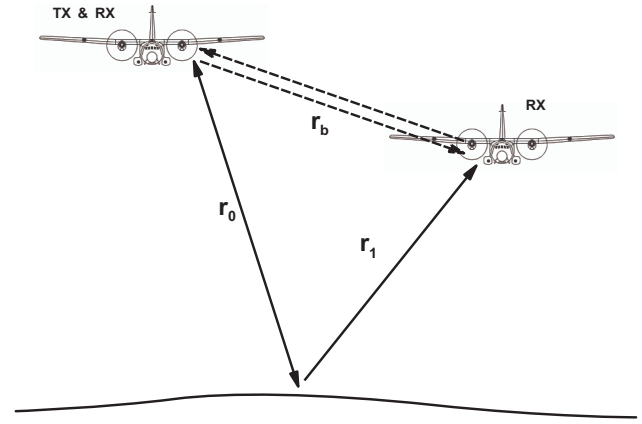


Fig. 5. Bistatic configuration with one transmitter and one separate receiver

B. Baseline measurement

Measuring the baseline continuously between two airborne platforms with the required accuracy of a fraction of a millimeter a two-way setup is used similar to that of the time transfer [3]. On both platforms a calibration signal is directly derived from the stable local oscillators (STALO) and then transmitted to the other platform. The received signal is down-converted by the other STALO and recorded for off-line compensation [8]. This is shown in Fig. 5.

As the baseline has to be determined with an accuracy of less than a millimeter for ranges up to several kilometers the phase noise contribution of the STALOs has to be taken into account [9]. The phase noise of the involved oscillators will limit the accuracy of range measurement. To investigate this effect the phase characteristic of the STALO is described by

$$\varphi_i(t) = 2\pi \int_0^t (f_i + \alpha_i(t')) dt' + \Delta\Phi_i(t) \quad (3)$$

$$= \Phi_i(t) + \Psi_i(t) + \Delta\Phi_i(t) \quad , \quad (4)$$

with f_i the STALO frequency, α_i the slowly varying frequency error and $\Delta\Phi_i(t)$ the phase noise of the oscillator. The broadcasted signal from both platforms looks like

$$x_i(t) = X_i \cos(\Phi_i(t) + \Psi_i(t) + \Delta\Phi_i(t)) \quad (5)$$

where i denotes the transmitter or the receiver.

The transmitter will record a demodulated phase from the remote receiver platform for the baseline measurement and compensation

$$\begin{aligned} \Phi_{bT}(t) &= \Phi_R(t - \tau_b) + \Psi_R(t - \tau_b) + \Delta\Phi_R(t - \tau_b) \\ &\quad - \Phi_T(t) - \Psi_T(t) - \Delta\Phi_T(t) \quad , \end{aligned} \quad (6)$$

with the baseline time delay $\tau_b = r_b/c$. The remote receiver, located up to several kilometers away from the transmitter, will record a demodulated phase of the direct signal from the

transmitter platform

$$\begin{aligned}\Phi_{bR}(t) &= \Phi_T(t - \tau_b) + \Psi_T(t - \tau_b) + \Delta\Phi_T(t - \tau_b) \\ &\quad - \Phi_R(t) - \Psi_R(t) - \Delta\Phi_R(t) .\end{aligned}\quad (7)$$

The length of the baseline can be determined from:

$$\begin{aligned}\Phi_{bR}(t) + \Phi_{bT}(t) &= \Phi_T(t - \tau_b) + \Psi_T(t - \tau_b) \\ &\quad + \Delta\Phi_T(t - \tau_b) \\ &\quad - \Phi_R(t) - \Psi_R(t) - \Delta\Phi_R(t) \\ &\quad + \Phi_R(t - \tau_b) + \Psi_R(t - \tau_b) \\ &\quad + \Delta\Phi_R(t - \tau_b) \\ &\quad - \Phi_T(t) - \Psi_T(t) - \Delta\Phi_T(t).\end{aligned}\quad (8)$$

It is assumed that both STALOs possess a slowly varying frequency error over time. Hence, the following assumption is applicable for short time delays: $\Psi(t - \tau) \simeq \Psi(t)$. If we further neglect the phase noise, (8) simplifies to

$$\Phi_{bR}(t) + \Phi_{bT}(t) \simeq \Phi_T(-\tau_b) + \Phi_R(-\tau_b). \quad (9)$$

From this the baseline can be calculated:

$$r_b(t) = -\frac{c}{2\pi(f_T + f_R)}(\Phi_{bR}(t) + \Phi_{bT}(t)). \quad (10)$$

As phase noise is present ($\Delta\Phi(t) \neq 0$) the accuracy of the measured baseline will show significant degradation. Consequently, (9) has to be expanded to

$$\begin{aligned}\Phi_{bR}(t) + \Phi_{bT}(t) &\simeq \Phi_T(-\tau_b) + \Phi_R(-\tau_b) \\ &\quad + \Delta\Phi_T(t - \tau_b) - \Delta\Phi_T(t) \\ &\quad + \Delta\Phi_R(t - \tau_b) - \Delta\Phi_R(t).\end{aligned}\quad (11)$$

Due to (10) the following relation exists between the standard deviation σ_r and σ_Φ :

$$\sigma_r = \frac{c}{2\pi(f_T + f_R)}\sigma_\Phi \quad (12)$$

with σ_Φ the standard deviation of the phase sum from (11). It is assumed that $\Delta\Phi_T$ and $\Delta\Phi_R$ are independent random variables having identical power spectra $W_\Phi(f)$. As the autocorrelation $R_{xx}(\tau) = \overline{x(t)x(t-\tau)}$ it is possible to write the standard deviation of the phases: $\sigma_\Phi^2 = 4(R_{\Phi\Phi}(0) - R_{\Phi\Phi}(\tau_b))$. By the Wiener-Khintchine theorem the autocorrelation can be determined from the phase noise power spectrum

$$R_{\Phi\Phi}(\tau) = \int_{-\infty}^{+\infty} W_\Phi(f) e^{j2\pi f\tau} df \quad (13)$$

Using (13) the standard deviation of the phase is

$$\sigma_\Phi^2 = 4 \int_{-\infty}^{+\infty} W_\Phi(f) [1 - e^{j2\pi f\tau_b}] df \quad (14)$$

$$= 16 \int_0^{+\infty} \mathcal{L}(f) \sin^2(\pi f\tau_b) df, \quad (15)$$

with $\mathcal{L}(f)$ the single-sideband phase noise. For high-quality crystal oscillators, $\mathcal{L}(f) \approx -160$ dBc/Hz (with respect to the carrier frequency) at offset frequencies $f \geq 1$ kHz. For

frequencies $f < 10$ Hz the phase noise $\mathcal{L}$ decreases by 30 dB per decade. In this region the RF phase noise is modeled as

$$\mathcal{L}(f) = N^2 \mathcal{L}_1 10^{-3 \log(f)}, \quad (16)$$

where $\mathcal{L}_1$ denotes the single-sideband phase noise at 1 Hz for a specific oscillator and N the ratio of the STALO frequency and the RF frequency. Using this approximation in (15) gives

$$\sigma_\Phi^2 = 16 N^2 \mathcal{L}_1 \int_0^{+\infty} 10^{-3 \log(f)} \sin^2(\pi f\tau_b) df \quad (17)$$

On airborne platforms one also has to consider that the effect of random vibration is to raise the phase-noise level of the oscillator. This degradation of phase noise is substantial and is caused by the vibration sensitivity of the stable local oscillators. An oscillator, accelerated by vibration, produces low level FM sidebands at the vibration frequency. For sinusoidal vibration the sideband level can be calculated as follows:

$$\mathcal{L} = 20 \log \left(\frac{\vec{\Gamma} \vec{a} f_0}{2 f_v} \right), \quad (18)$$

with $\vec{\Gamma}$ the sensitivity with typical values in the range of 10^{-9} Hz/g to 10^{-10} Hz/g, $\vec{a}$ is vibrational acceleration, f_0 the center frequency and f_v the vibrational frequency. On airplanes a random-vibration specification (power spectral density [PSD] vs. vibration frequency) starts at 5 Hz and stops at approx. 2 kHz. The degradation of the phase noise level can be up to 45 dB in this frequency range.

IV. CONCLUSION

Technology of today allows to maintain a sufficiently high time coherence between two separated sites. Experiments with two-way communication links via satellite were able to achieve a variance of less than 1 ns in time for stations separated over several hundreds of kilometers. Using the common-view method for short baseline with low-cost GPS-units, time variance of less than 5 ns can be expected for moving stations. Frequency coherence depends on the processing and can range from μ s to several seconds, as it is the case for interferometric SAR, where the baseline has to be known in the order of several millimeters. It was shown that the phase noise contribution has a wide influence in determining the baseline precisely for ranges beyond several kilometers.

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