UGS Localization on an Electronic Battlefield

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Abstract:
Presented article is reviewing technological possibilities of the passive sensor localization in an unfamiliar environment by means of different methods. The article is describing alternate approach to solution of this problem. The article is devoted to description of design and characteristics of the system for Unattended Ground Sensor – UGS localization based on the phase interferometer defining direction to the signal source pursuant to measuring of the phase difference of the received signal by two different antennae and knowledge of the signal frequency. In the article, the design of the antenna array, the phase interferometer and the signal line design are presented. The designed principle of the received signal numeric phase difference measurement and consequential localization algorithms are described as well. The article closure is dedicated to the system design of the director system intended for UGS localization. Behavior of designed algorithms for the numerical signal processing generated in the Matlab mathematic environment is graphically presented here.

1. Introduction

Problems of sensors for detection of presence and movement of person, vehicles and other objects cover many different research areas. It concerns selection areas of the given sensor function principles first of all, transmission mode of information, power supply implementation, method of the sensor transport to the service area etc. The sensor localization problem in the given area with the required accuracy is another, not less important research area. Although UGS miniaturization goes forward very fast, even in the future it will be difficult to integrate GPS antenna to the developed UGS of the acceptable size. Moreover, for the strategy of area stationing of UGS in the service area in big quantities, integration of GPS receiver into any unit looks to be economically inefficient.

Let us consider the following situation for analysis of sensor localization possibilities. N = 10 sensors are placed to the circular service area of the diameter D_Z = 5km (by dropping them from an airplane, for example). The sensors are transmitting messages in the beforehand-defined intervals in the frequency band of f = ca 150MHz. The length of the messages is 60ms. It is our task to define the sensor positions by the passive system (direction finder) with the standard deviation of σ_R = 25m. The immediate localization is not required, but evaluation of the overall situation during 24 hours of the direction finder activity is required. Furthermore, the total emitted power of individual sensors P_{sen} = 1W emitted by the 1/4 λ unidirectional antenna with the vertical polarization is defined. [4],[5],[6],[7]

2. Options for UGS localization

Generally, it concerns localization of the active device (signal source) by means of the passive system. This task can be executed by the basic method of signal source localization, which is triangulation, or by means of complicated signal source localization methods. The TDOA (Time Difference Of Arrival) method can be categorized to this class. It is necessary

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to define the method for determination of direction to the signal source when using the triangulation method. The amplitude method or the phase-measuring method appears to be the available methods for direction determination.

2.1 Application of triangulation with the amplitude direction determination method

This method is based on determination of direction to the signal source from at least two position-different receiving stations and on subsequent source position calculation by the triangulation method [1]. In the case of the off-line signal source position evaluation, it is possible to use only one direction finding station that executes consecutive source direction findings from several different locations. The situation is shown in the figure 2.1.

In principle, direction determination by means of the amplitude methods is the spatial signal source filtration by the receiving antenna that is described by the antenna radiation pattern. Regarding the situation under consideration, for the source localization accuracy σ_R the direction should be determined with at least the accuracy of:

$$\delta = 2.\arctan\frac{d/2}{S} = 2.\arctan\frac{12.5}{5000} = 0.3^{\circ} \qquad (1)$$

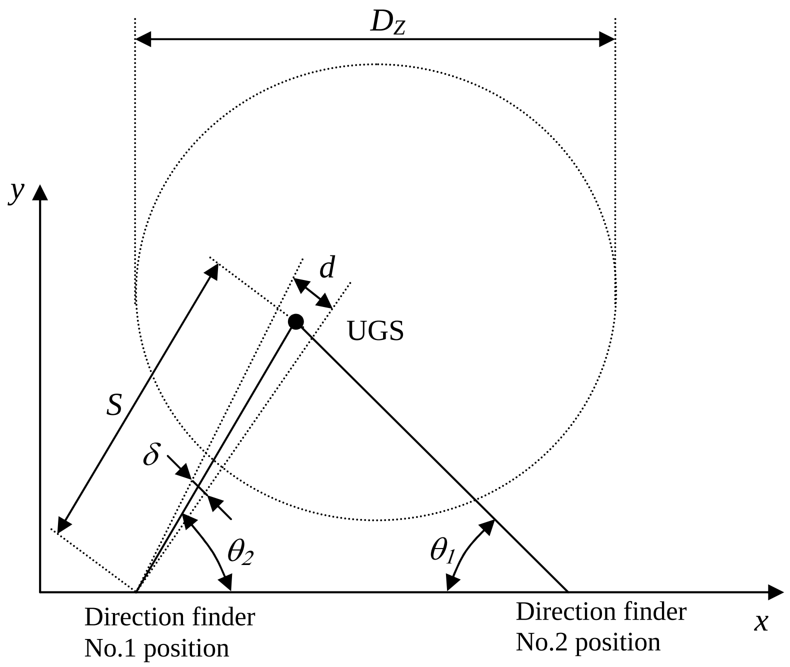

Fig. 2.1 Triangulation source localization method (position of the No. 1 direction finder)

If we consider the sensor frequency f = 150MHz (λ = 2m) and the antenna radiation pattern of the direction finder antenna in the horizontal plane γ = 5° or (if you like). 0.1rad (suitable for using the amplitude direction determination method on “minimum” or “equal-signal“ methods), the antenna dimensions in the azimuth plane will be approximately:

$$A = \frac{\lambda}{\gamma} = \frac{2}{0.1} = 20m$$

It is obvious; such a sizable antenna is quite unsuitable for the field use, where high mobility of the direction finder, covert activity, etc. have to be maintained. Necessity to search for the signals in the azimuth (antenna has to be rotated) is another disadvantage of the triangulation using above mentioned amplitude methods. It presents demanding technological solution of the antenna array but also the substantial decrease of the signal source detection probability, which is more important. Usage of the sensor triangulation localization method by means of the amplitude direction determination method so that the requirements outlined in the starting situation are fulfilled looks to be not realistic.

2.2 TDOA method application

With respect to their number (two frequency changes during the sensor transmission), the sufficient integration of received signals and even measurement of their arrival time with accuracy at least δ_T = 100ns cannot be provided (such a accuracy corresponds to the requirement for determination accuracy of δ_{ZP} = 180ns). Considering the above-mentioned conditions, the TDOA method is hardly usable for localization of the given sensors.

2.3 Application of the triangulation method with direction finding using the phase interferometer

Localization of individual sensors is solved by the triangulation method again, however the phase interferometer is used for finding direction to individual sensors. The phase interferometer is eliminating most of negative properties of the amplitude methods (it concerns antenna characteristics requirements above all).

The phase interferometer determines direction to the signal source by means of measuring the phase difference of the signal received by two different antennae and knowledge of the signal frequency. In case of the model situation mentioned at the beginning of this chapter, the requirements for the phase interferometer can be summarized in following points:

- With regards to the sensor signal wavelength (λ=2m), the antenna base length (antennae distance) d_b=1m (λ/2) is sufficient for the unambiguous direction measurement.
- Precarious knowledge of the received signal frequency does not require its measurement, so this measurement would not contribute to the total error of direction finding.
- The antenna radiation pattern width γ can be in order of magnitude of tens of degrees (easy design in the given frequency range).
- With regard to the direction determination accuracy of δ = 0.3° relatively stark requirements for measurement of the received signal phase difference measurement $\Delta\varphi$, or for the required *S/N* ratio of the received signal.

It is obvious furthermore, that when using this method, searching for sensors in the azimuth (antennae do not rotate) and communication between receiving stations are dropping out and demands for position determination accuracy of receiving stations is markedly reduced. In the case that the direction finding results can be processed off-line, there is the option to use one direction finder only that executes direction finding from number of different positions subsequently. If the measurement is executed from at least three different positions, so called auto calibration of the direction finding system can be utilized. It means in practice that demands for the initial antenna orientation on the reference azimuth are substantially reduced.

After considering characteristics of all localization options of the particular sensors, utilizing of the triangulation method of particular sensor localization together with direction measurement by the phase interferometer appears to be optimal.

3. System design of the direction finder

For solving the above-mentioned task, the passive direction finder utilizing the triangulation method with the successive direction measurement of direction to the sensors from at least three stations of different positions by the phase comparative method (with the phase interferometer) will be used. The location of individual stations (measurement locations) will be determined by means of the GPS receiver that will be integrated in the direction finder. The initial orientation of the directional antenna at individual direction finding stations will be provided with the coarse azimuth deduction of the service area center. In computation of individual sensors location, the "superfluous" third measurement will be used (two direction finding stations are sufficient for triangulation) that would ensure the auto calibration characteristics of the system.

The relation for signal source (sensor) direction finding with the θ phase interferometer is defined by the following equation:

$$\theta = \arcsin\left(\frac{\Delta\varphi.\lambda}{2\pi.d_b}\right), \qquad (2)$$

where: $\Delta\varphi$ is the measured phase difference,
λ is the received signal wavelength,
d_b is the antenna base length.

Then, equation for the standard deviation of the phase σ_φ measurement (requirement for the direction finder phase measurement accuracy) can be derived as:

$$\sigma_\varphi = \frac{\sigma_\theta.2\pi.d_b.\cos(\theta)}{\lambda} \quad , \qquad (3)$$

where: σ_θ is the standard deviation of the source direction measurement.

In figure 3.1, there is the diagram of relationship between σ_φ and the angle θ for the defined value σ_θ = 0.15°, wavelength $\lambda = 2$m, base length d_b = 1m and range of measured azimuths θ = +/- 60°. It is obvious from the diagram; the direction finder has to able to measure the phase difference with the standard deviation of $\sigma_\varphi = 1°$.

In the figure 3.2, there is the simulation of location calculation for 10 randomly spread sensors in the circular area with diameter of 5 km by the triangulation method with two positions of the direction finder, which is measuring phase difference with $\sigma_\varphi = 1°$, or azimuth with $\sigma_\theta = 0.15°$, if you like The measurement was executed 10x, whereas the phase difference $\Delta\varphi$ measurement has the character of the normal probability distribution. The resulting locations of particular sensors (after 10 measurements) were determined with the circular position error σ_R determined according to the equation $\sigma_R = \sqrt{\sigma_x^2 + \sigma_y^2}$ as follows:

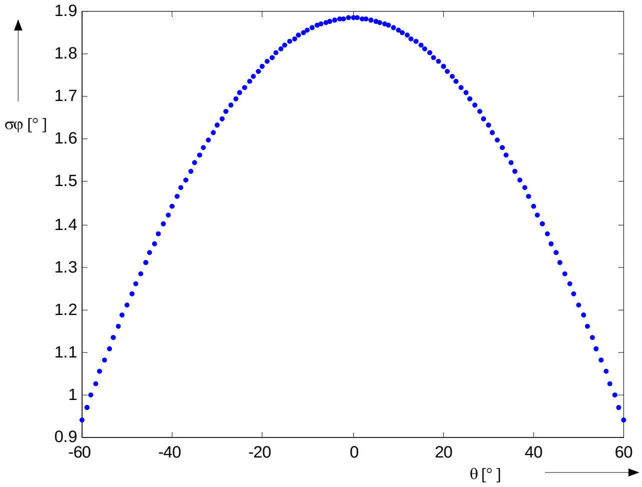

Fig. 3.1 Relation σ_φ to angle θ

1. senzor ……σ_R = 6.6m (21m)
2. senzor ……σ_R = 7.3m (23m)
3. senzor ……σ_R = 4.3m (13m)
4. senzor ……σ_R = 17.6m (55m)
5. senzor ……σ_R = 7.2m (22m)
6. senzor ……σ_R = 7.7m (24m)
7. senzor ……σ_R = 7.8m (22m)
8. senzor ……σ_R = 8.7m (27m)
9. senzor ……σ_R = 6.6m (21m)
10. senzor ……σ_R = 7.0m (22m)

By the multiple measurements, all locations were determined with accuracy that is not second to the required sensor location determination error σ_R = 25m.

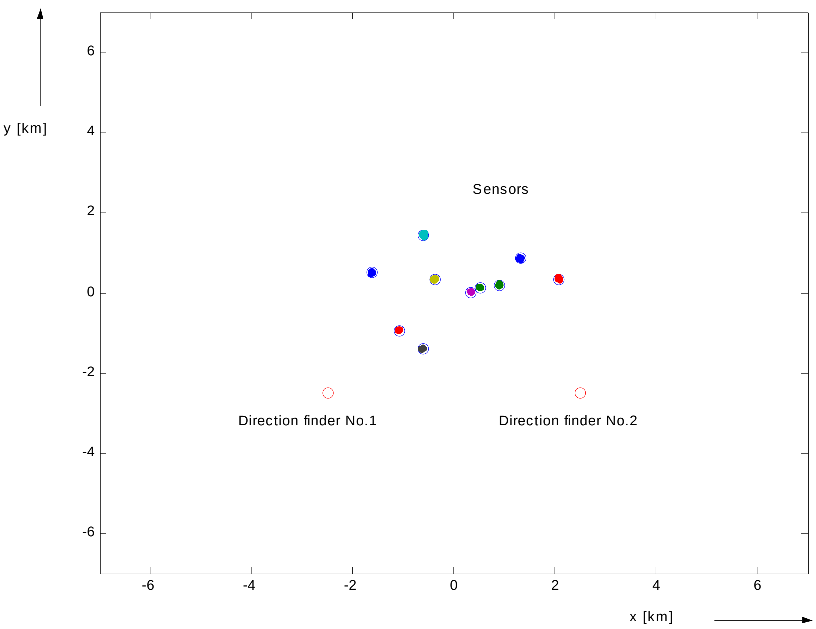

Fig. 3.2a Sensor location simulation

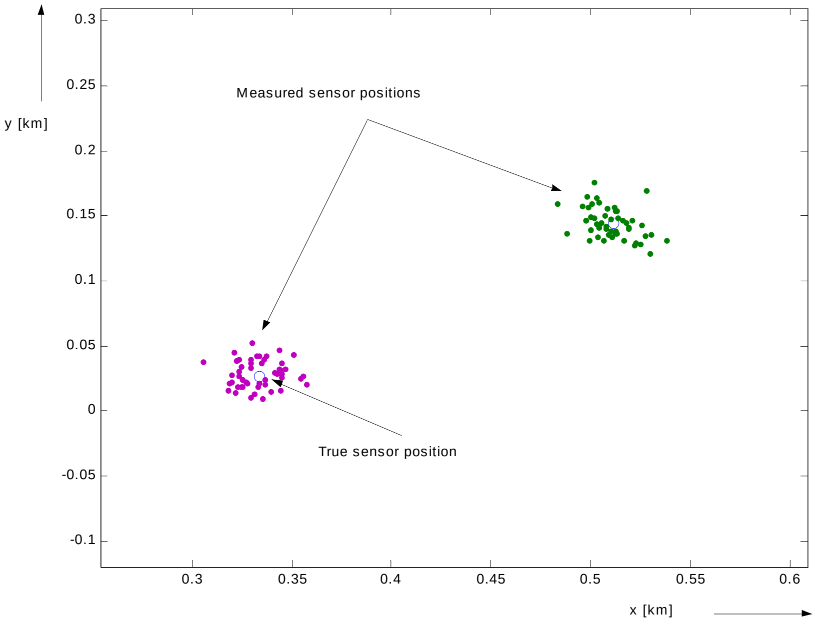

Fig. 3.2b Sensor location simulation - detail

From the physical point of view, the phase measurement error is caused by presence of the noise. If the voltage will be measured on output of the particular antennae in the direction finder for obtaining the phase difference value *Δφ*, then σ_φ is equal to:

$$\sigma_\varphi = \arcsin\left(\frac{U_N}{U_S}\right) = \arcsin\left(\sqrt{\frac{N}{2.S}}\right), \qquad (4)$$

where:

- U_N is the noise voltage,
- U_S is the signal voltage,
- N is the noise output and,
- S is the wanted signal output.

If σ_φ = 1° is required, then the required signal/noise ration should be *S/N* = 1640 = 32dB according (3) at input of circuits. This *S/N* ratio is determining for the design of the direction finder receiver. In respect of the received signal wavelength λ = 2m, output of the signal transmitted by the sensor P_{sen} = 1W, distance between the sensor and the direction finder *R* ~ 5000m, antenna gain of the direction finder G_z ~ 5dB and received signal bandwidth *B*, the *S/N* value is attainable even at the relatively high noise number *F* of the direction finder receiver. So, no excessive requirements are posed on realization of the receiver.

Another error of phase difference determination is created by the measurement self. For minimization of this error, it is necessary to choose the quantifying level of the phase difference at least 10 times lower then the error caused by the *S/N* ratio. This level should be at least 0.1° in our case.

3.1 Realization scope of the direction finder receiver

From the practical point of view, the direction finder receiver can be implemented in two ways, in the course of adhering to the above-mentioned requirements. It is the first implementation option to measure the phase difference directly on the carrier frequency of the received signal (ca 150 MHz). The block diagram of such a receiver is described in the figure 3.3.

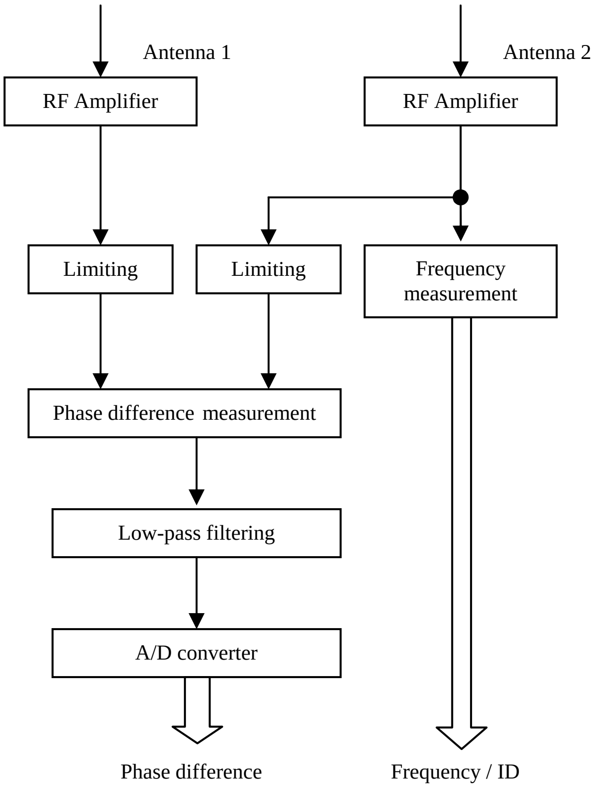

Fig. 3.3 Block diagram of the receiver

The received signal from both antennae is amplified, limited and fed to measurement circuits of the phase difference. The output voltage from the circuit goes through a low pass filter to A/D converter. Concurrently, a part of the antenna signal goes to the frequency determination circuits. There, one of *n*-possible signal frequencies transmitted by the sensor is evaluated. Extensive line of commercially available phase discrimination circuits can be used for phase difference measurement.

If the 16 bit converter will be used for digitalization of output voltage from phase difference measurement circuits (360/0.1 = 3600 levels, which is 12 bits, are sufficient for 0.1° phase resolution) with the sample frequency F_{sf} = 10 kHz. 600 phase measurements would be executed in 3x20ms (length of the transmitted signal), which is sufficient for calculation of the mean value of the phase difference.

There is the second option of implementation, the frequency of the received signal can be converted to the lower frequency range, this signal can be digitized and phase difference computed by means of the complex Fourier transformation (digital receiver is used).

3.2 Realization scope of the receiving antenna

By reason of preserving high mobility of the direction finder and high speed of its preparation to operation, there is an assumption that receiving antennae are implemented with the 4 elements of the Yagi type maximum with the direction radiation pattern in the horizontal plane of 65° (that is sufficient for reception from the defined area of sensor locations) and with the gain of G_z = 5dB.

4 Conclusion

Task solution of localization sensor with the above-mentioned parameters and under defined conditions is optimally contrivable by the passive direction finder utilizing the triangulation method of signal source localization with measuring the direction to the signal source by means of the triangulation comparative method.

Analysis of properties and system characteristics of the direction finder stated in this article are sufficient for its HW design. Practical verification of every direction finder particular part's functionality is necessary for follow-up works. In practice attained results of the whole UGS localization system will be presented continuously. [1],[2],[3],[8]

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