

1999

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1999. 12. 30.

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1.

가.

.
. FCC E-911
2001 10 100 m
67

2.

o	
o (AOA) - - MLM, - MUSIC	
o - TOA - TDOA	

o -	
o	

3.

- (GPS, Loran- C, TOA, TSOA, TDOA)
- (, MLM, , MUSIC) , TDOA (Chan's Method),

4.

IMT - 2000 가 119 가

5.

- 119

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SUMMARY

. Title

A study on the position location estimation in mobile communications.

. Objectives and Importance of Research

Today, the primary motivation for implementing position location is conformance with FCC regulations, which are concerned primarily with the ability to locate mobile telephones originating emergency phone calls. This mandate represents a major deployment and operations challenge to wireless service providers, particularly those that are highly financially leveraged to pay for their spectrum and new infrastructure. However, there are also other position location applications that are of interest to service providers. These applications provide carriers the opportunity to differentiate themselves from competitors through better emergency services and additional services such as mobile yellow pages, equipment tracking, and position dependent billing. Other possible services include location-specific advertising (e.g., restaurant/hotel guides), personnel tracking, and navigation assistance. For equipment service providers and carriers, this new capability represents as \$8 billion market.

Many existing wireless location systems, such as the Global Positioning System (GPS) and Loran C, make use of radiolocation techniques. With these technologies the MS

formulates its own position, which can be relayed to a central site. Some approaches employ a cellular networks as the transport mechanism for relaying the location estimate. The signal measurements are used, for example, to determine the length and/or direction of the individual radio paths, and then the MS position is computed from geometric relationships.

Radiolocation systems can be implemented in one of two ways. With the first approach, the MS uses signals transmitted by the BSs to calculate its own position, as in GPS. With the second approach, the BSs measure the signals transmitted by the MS and relay them to a central site for processing. The second approach has the advantage of not requiring any modifications or specialized equipment in the MS handset, thus accommodating the large pool of handsets already in use in existing cellular networks.

The primary emphasis of this research is on presenting an effective position location estimation method of meeting the emergency service requirements.

These requirements present many technical challenges, such as the choice of location technology and the influence of radio propagation and coverage on accuracy.

. Contents and Scope

- Performance analysis of angle-of-arrival(AOA) estimation methods such as beamforming, Maximum Likelihood Method(MLM), and Multiple Signal Classification(MUSIC).

- Presentation of a variety of network-based position location method such as Time-of-Arrival (TOA), Time-Difference-of-Arrival (TDOA), etc.
- Characteristics analysis of position location method based on measurement of signal strength transmitted by mobile station.
- Introduction to the effective position location method that is applicable to next-generation mobile communication system.

. Research Results

- Introduction to the position location methods using the existing cellular radio network.
- Introduction to performance benchmarking for wireless location systems.
- Performance analysis of angle-of-arrival estimation methods such as MLM, LPM, and MUSIC through computer simulations.
- Presentation of Chan's method based on intersections of hyperbolic curves defined by TDOA for effectively locating a signal source.
- Presentation of position location technique based on signal strength comparison and database system.

5. Expected Contribution and Application

- Emergency 911 service
- Monitoring system for fraud detection
- Location-sensitive billing
- Cellular system design
- Fleet management and intelligent transportation systems (ITS)

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1

GPS(Global Positioning System) 가 FCC
(Federal Communications Commission) PCS

(E- 911) .
2001 100 m
67 [1].

가

RADAR, SONAR, , ITS

가 ()
가 , 가

[illegible]

[2].

가

GPS, LORAN

TOA(Time of

Arrival), TDOA(Time Difference of Arrival)

, AOA(Angle of Arrival)

,

가

2

GPS, LORAN-C

3

AOA, TOA, TDOA

, 4

. 5 , 6 , 7

, , 8

2

GPS[3] Loran- C[4]

. GPS 가

Loran- C

.

1 GPS

1. GPS

GPS[3]

GPS , 가

. GPS

93 , 95

.

- 3 ,

- 24

- ,

- 가

- : WGS- 84(World Geodetic System

of 1984)

GPS (SPS: Standard Positioning System)
 (PPS: Precise Positioning System) ,

.

, 가 , (SA :
 Selective Availability)

. 가 100 m

, 156 m 340 nsec

. 가

가 가

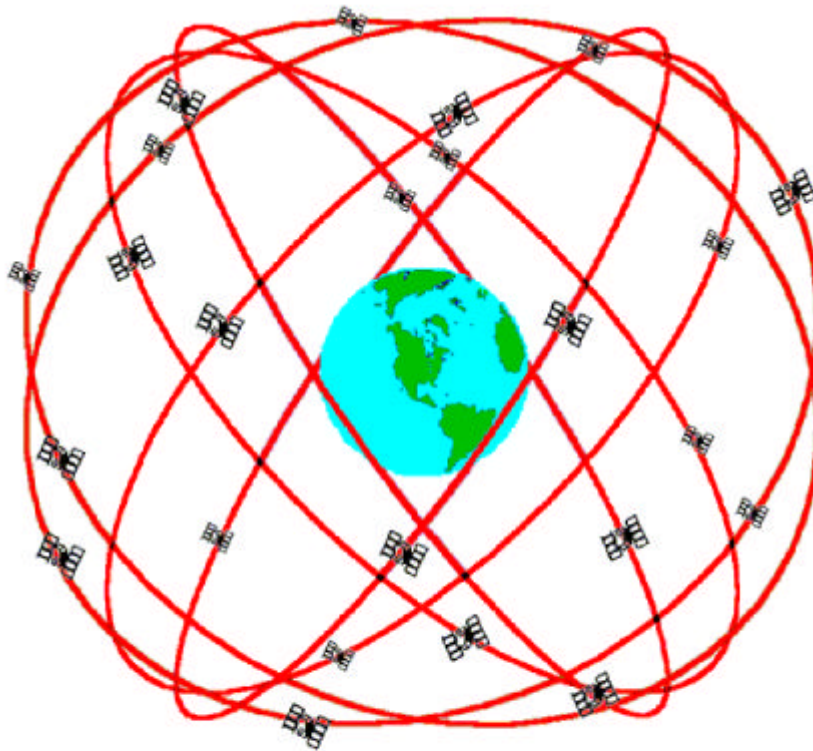
,

가

. 22 m , 27.7 m

, 100 nsec . (2.1) GPS

[5].



GPS Nominal Constellation
24 Satellites in 6 Orbital Planes
4 Satellites in each Plane
20,200 km Altitudes, 55 Degree Inclination

(2.1) GPS

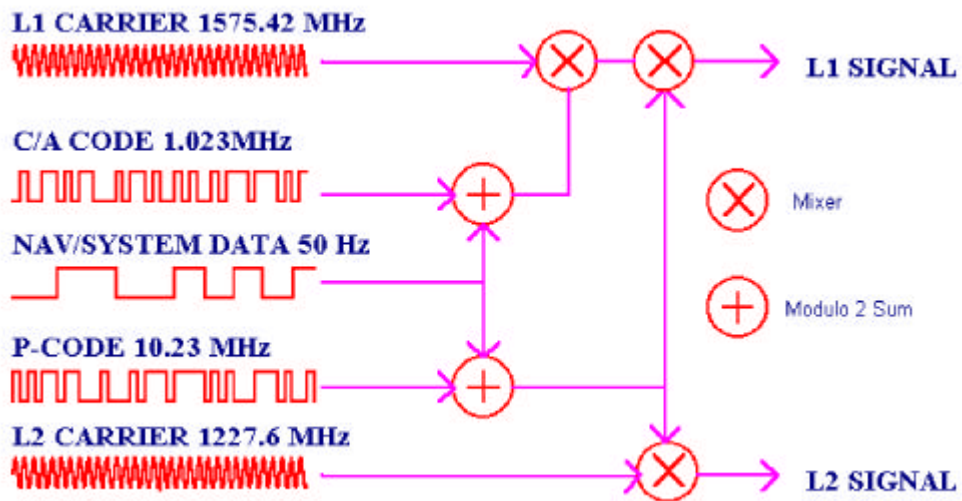
가. GPS

GPS ,
 3 , , , ,
 .

1)

24 GPS , GPS

가 2
, PRN (Pseudo Random Noise)
. 24 21
3 가 12 .
(Herix Array) 가
15 dB . GPS
20,183 km 0.03 가
55 .
6 4 24
. GPS
11 58 .
GPS 가 5
. 2 L ,
L1(1,575.42 MHz) L2(1,227.6 MHz) , L1 P
(Precise Code) C/A (Coarse/Acquisition) , L2 P
. 가 , L1, L2
.

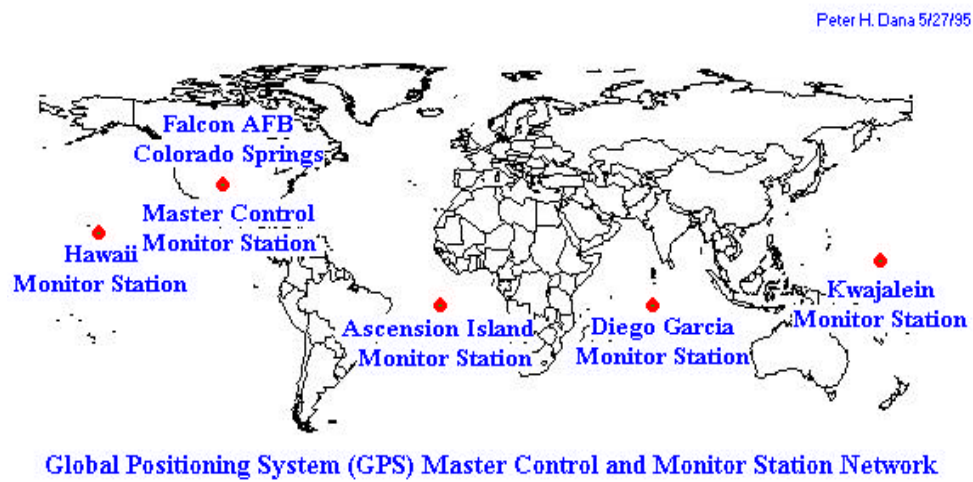


(2.2) GPS

2)

3가
 , (MCS: Master Control Station)
 (MS: Monitoring Station) (GA:
 Up-link Ground Antenna) . GPS
 , Colorado Springs
 .
 , GPS가
 5
 GPS , GPS

3 S- band(up- link 1783.74 MHz,
down- link 2227.5 MHz)



(2.3) GPS

3)

GPS

, GPS

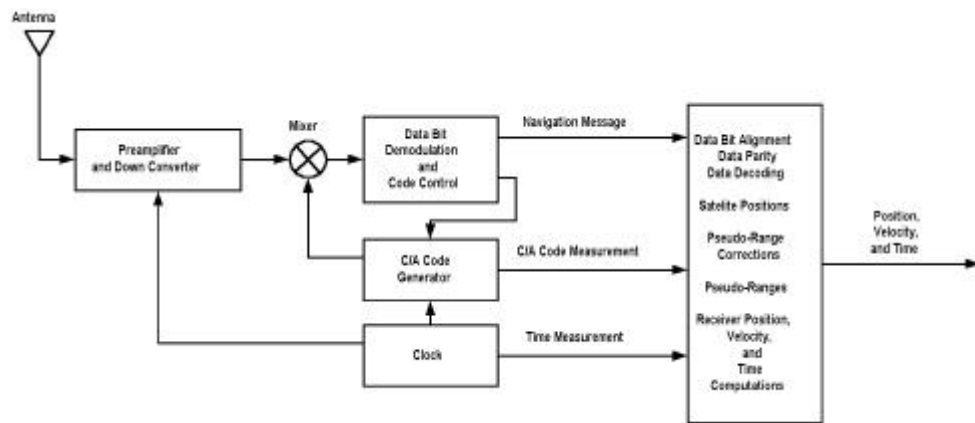
. 2

3

4

3

4



(2.4) GPS

GPS
가
GPS

(= ×).

GPS

GPS
3가
,

(SA : Selective Availability)

가 . GPS

(2.1) .

(2.1) GPS

	20 m (SA:50 100 m)	
	10 m	
	2 50 m	
	2 30 m	
	0.2 3 m	
	0.1 3 m	

1) (Range Error)

, 5 10 m .

가
가 가

PDOP가 3 이하인 경우, 15 m CEP(Circular Error Probability), 50% 15 m

가 ,

. (2.2) GPS (2.3)

(2.2) GPS

(: 1,000)

1992	16	1.2	5.6	9
1993	17	1.8	8.4	13.5
1994	19	2.4	12.6	20.25
1995	21	4	18.9	30.375
1996	25	6	28.4	45.6
1997	26	10	50	60
1998	28	20	100	75
1999	30	40	150	90
2000	32	80	200	105
2001	34	100	300	120
2002	35	150	500	135
2003	36	200	1,500	150
2004	37	300	2,000	165
2005	38	500	2,500	180

(2.3) GPS

SPS	: 100 m : 140 m : 340 ns	24 GPS 21 98 % , 7.5
PPS	: 21 m : 29 m : 100 ns	

GPS/PPS

-
-
-

가 GPS/PPS

가. (SPS)
SPS

. SPS (L1) ,
PRN 1.023 Mbps C/A
.
, 가 100 m . SPS
SA
.

. (PPS)
 PPS , 가
 . ,
 .
 PPS P (Precise
 Pseudorandom Tracking Code) . P
 가 22 m .

3. GPS

GPS (2.4)
 . 1 가
 가 4 GPS
 .
 15 30 m 가 가 .
 (SA)
 100 m .

(2.4) GPS

(Positioning)	GPS 1	15 30 m 100 m(SA)	가
DGPS (Differential GPS)		1 5 m	
(Static Survey)	2 GPS	m	가 가
RTK (Real Time Kinematic)	2	1 2 cm	가

가. DGPS

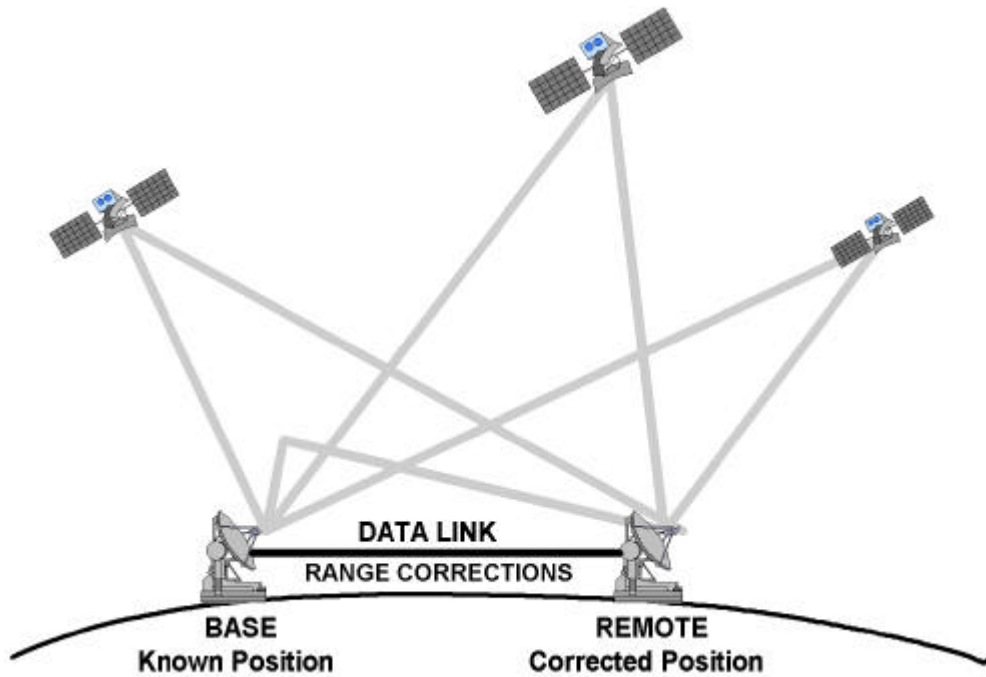
DGPS(Differential GPS)

2 가 .
1 .

(Range Correction)

RTCM SC- 104 ,
가
가 m ,

1 m 가 .
 ITS GIS . DGPS
 FM 가 ,
 DGPS .



(2.5) DGPS

· (Post Processing Static Survey)

, cm

L1/L2

가

GPS

가 , Bernese
GPS S/W ,
1 2(20 ppb: part per billion)
.

. RTK(Real Time Kinematic)

1 2 cm
RTK(Real Time
Kinematic) . RTK
가 가
DGPS , RTK
가 DGPS
가
가 RTK 가 가
DGPS . GPS
DGPS RTK가 , GIS ,
가 RTK .

4. GPS

가.

Loran- C, OMEGA, VOR/DME, TACAN

, ,
.
, GPS GLONASS가

GPS
 SPS , 가 가
 DGPS ,
 가 /
 , GLONASS
 GPS/GLONASS 가
 GPS
 GLONASS 가 ,
 GPS
 가 .
 GNSS(Global Navigation Satellite System) 1, 2
 GNSS-1 GPS GLONASS
 (GEO) ,
 EGNOS(European Geostationary Navigation Overlay Service)
 , 2000 , 2003 4
 GEO
 INMARSAT-3 MSAT ,
 GPS/GLONASS
 가 .
 GNSS-2 GNSS-1
 ENSS
 (European Navigation Satellite System),
 ESANSS(Europe and South-America Navigation Satellite
 System)

GPS

.

.

1)

GPS 가
, 가

(GNSS: Global Navigation Satellite System)

ESA(European Space Agency)

.

GNSS GPS 100 m 5 10 m

,

가 ,

가 가 .

,

,

.

가 .

2)

,

GLONASS . GLONASS

가

가 . 3 GLONASS

RF

3)

(NASDA:National Space Development
Agency of Japan) 2002
700 3

10 m
GPS

GNSS

GNSS-1

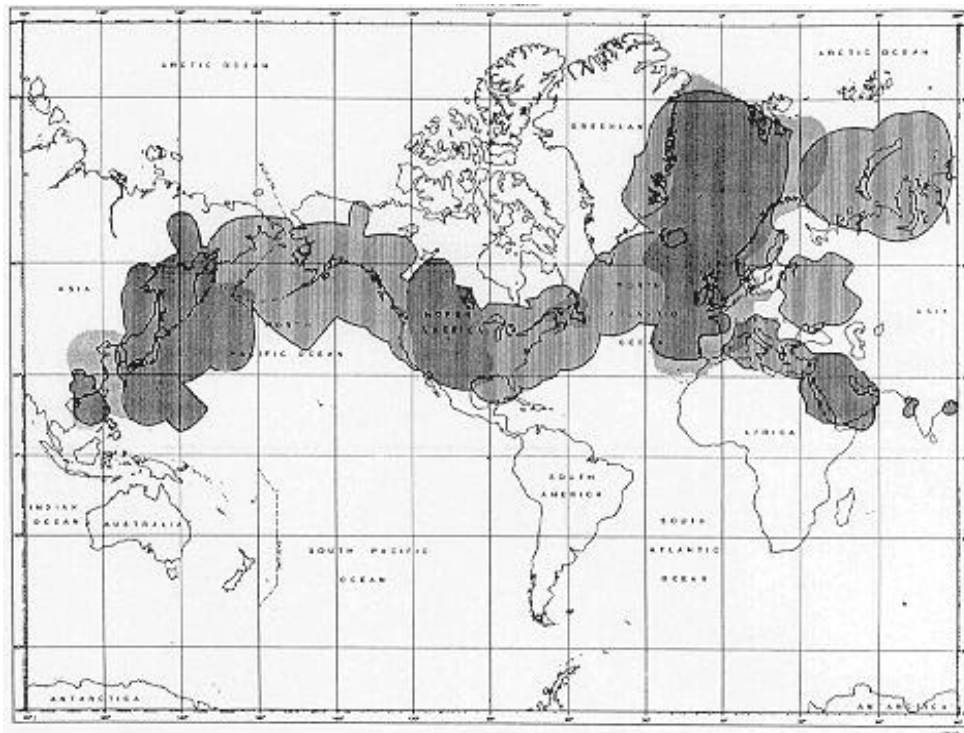
MTSAT (Multi-functional Transport Satellite)

(MSAS: MTSAT Satellite-based
Augmentation System)

2 Loran- C

Loran- C[4]

Loran- C
Chayka 가 (2.6) Loran- C



(2.6) LORAN- C

Loran- C

Loran- C

. Loran- C 가
 . 100 kHz 8
 (=1 burst) . Loran- C 0
 가 .

1. Loran

(chain)

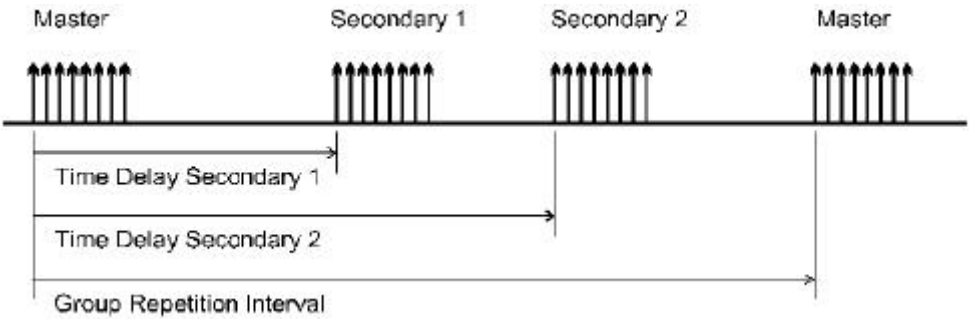
Loran- C

(Master transmitter) 2 5 (slaves,

secondaries transmitter) . 8
()

8

(Group Repetition Interval, GRI) . 40 ms 100 ms
GRI 가 . (2.7) Loran- C



(2.7) Loran- C

Loran- C GRI
.

가 가 가
($c=3 \times 10^8$ m/s) 가
(= \times).
가 .

가 .

(GMT) 가
가

2. Loran- C

Loran

$$\text{Envelope}(t) = A \left(\frac{t}{t_p} \right)^2 e^{-2(1 - \frac{t}{t_p})} \quad (2.1)$$

$$\text{carrier}(t) = \cos(\omega t + \text{phasecode}) \quad (2.2)$$

Loran- C

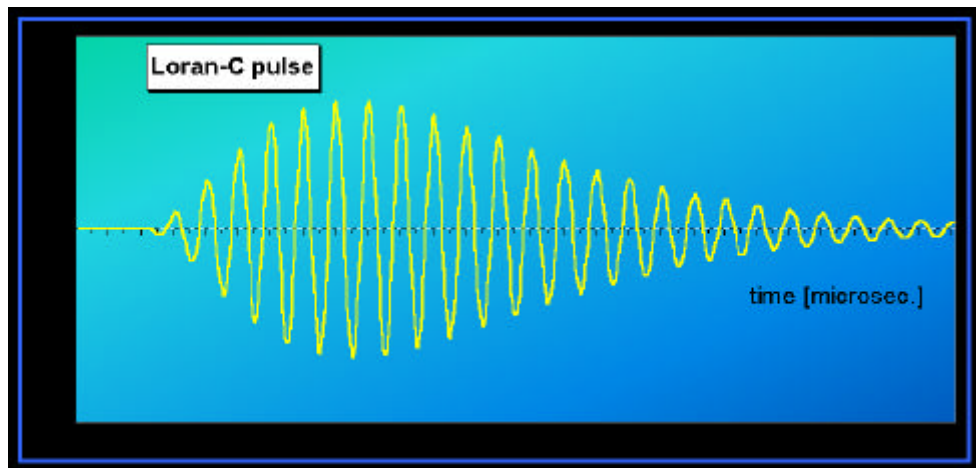
$$e(t) = \text{envelope}(t) \times \text{Carrier}(t) \quad (2.3)$$

t , t_p 65 μs

2 \times 100 kHz . phasecode 0

. 1/(100 kHz) 10

μs .

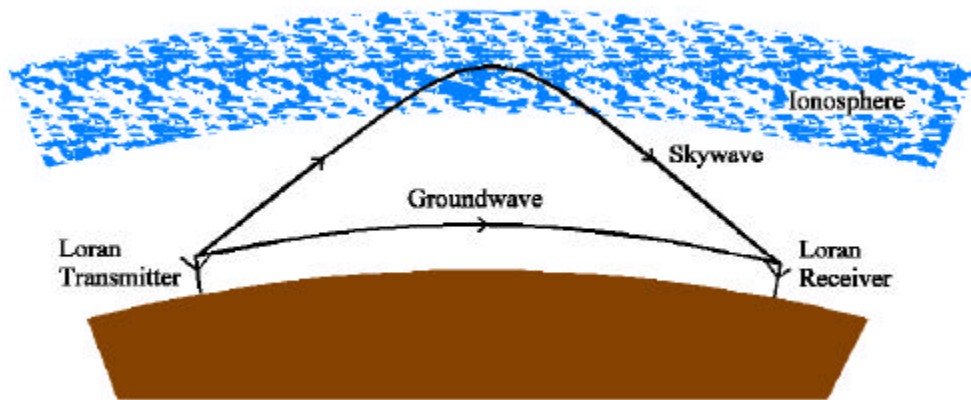


(2.8) Loran- C

가
(0)가 가 .
가 . 3
가 .

3 Loran- C

Loran- C 100 kHz .
(kilometric) LF(Low Frequency) .
.
(groundwave) .
(skywave) .



(2.9) Loran- C

100 kHz

60 1000 km

. Loran- C

(2.5)

LORAN- C

[6].

(2.5)

Loran

(8 35 , 1998)

Chain /Station	Location	Distance (Miles)	SNR (S/N)	Time Difference (ns)
5930M	Caribou, ME	1076	5	00000000
5930X	Nantucket, MA	1000	2	12697998
5930Y	Cape Race, CAN	1775	- 13	32510363
5930Z	Fox Harbour, CAN	1673	- 11	44815039
5990M	Williams Lake, CAN	1644	- 19	00000000
5990Y	George, Washington	1502	- 12	28164724
7980M	Malone, FL	867	12	00000000
7980W	Grangeville, LA	859	11	12763788
7980X	Raymondville, TX	1240	1	29446192
7980Y	Jupiter, FL	1224	- 5	47121889
7980Z	Carolina Beach, NC	878	8	61598643
8290M	Havre, MT	1064	3	00000000
8290W	Baudette, MN	455	20	11515072
8290X	Gillette, WY	819	14	27766654
8290Y	Williams Lake	1644	- 17	48304428
8970M	Dana, IN	245	23	00000000
8970W	Malone, FL	867	9	17701052
8970X	Seneca, NY	635	17	33255871
8970Y	Baudette, MN	455	21	48882409
8970Z	Boise City, OK	852	14	66932920
9610M	Boise City, OK	852	13	00000000
9610V	Gillette, WY	819	14	13703790
9610W	Searchlight, NV	1462	- 15	31890672
9610X	Las Cruces, NM	1223	- 3	44038690
9610Y	Raymondville, TX	1240	1	58109451
9610Z	Grangeville, LA	859	13	69340604
9940M	Fallon, Nevada	1546	- 15	00000000
9940W	George, Washington	1502	- 11	13563117
9940X	Middletown, CA	1749	- 8	29208822
9940Y	Searchlight, NV	1462	- 14	41517117
9960M	Seneca, NY	635	17	00000000
9960W	Caribou, ME	1076	- 11	16173428
9960X	Nantucket, MA	1000	4	28933526
9960Y	Carolina Beach, NC	878	7	43529247
9960Z	Dana, IN	245	23	55068549

3

.

[57].

(DOA : Direction- of- Arrival)

(AOA : Angle- of- Arrival)

.

,

(Lines- of- Bearing)

가 .

,

가 .

ranging (), range- sum (

), range- difference () .

가 .

.

.

d

$$d = c \tau$$

τ

, c $3 \times 10^8 m/s$.

가

. (TOA : Time-of- Arrival)

.

TOA

.

가

가

가

Pseudo- system

.

.

(Relative- sum)

.

.

T SOA(Time- Sum- of- Arrival)

.

(Relative

difference)

.

(TDOA : Time- Difference- of- Arrival)

.

가

,

가

TDOA

(trilateration) (multilateration)

3

2

가

PCS

가

가

가

PCS

1

DOA

Lines- of- Bearing()

DOA

DOA

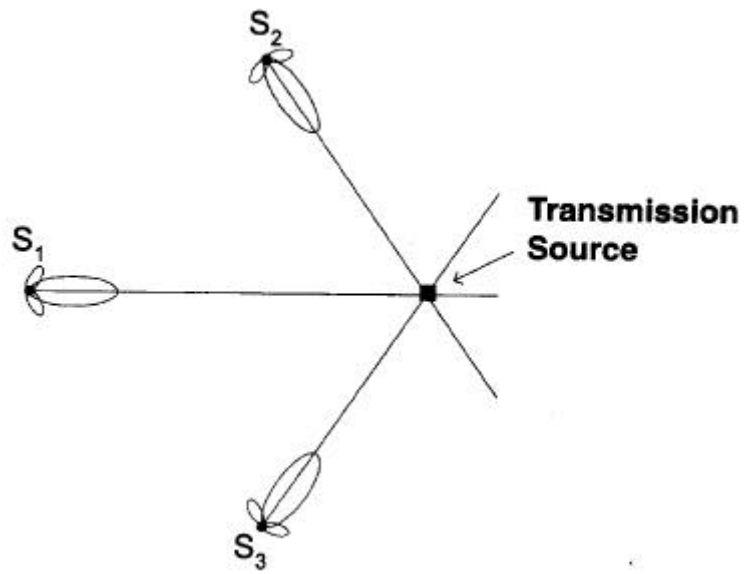
(3.1) 2

DOA

DOA

DOA

가



Lines- of- Bearing()

DOA

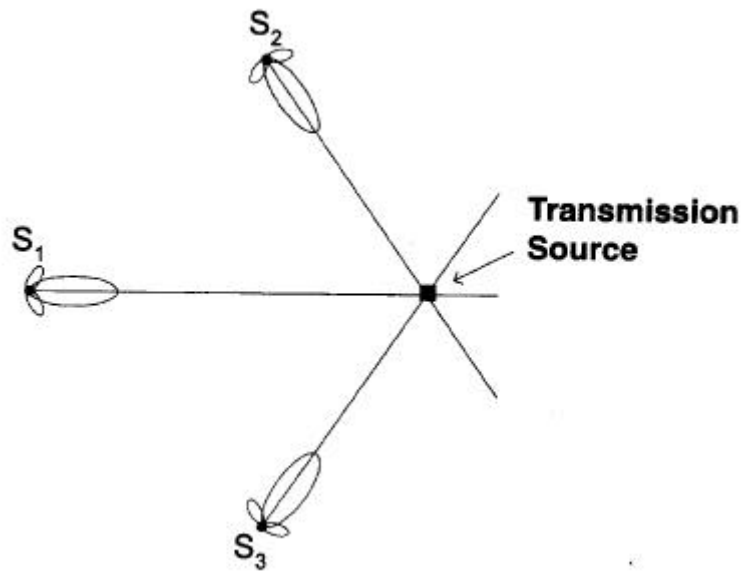
DOA

$$(3.1) \quad 2$$

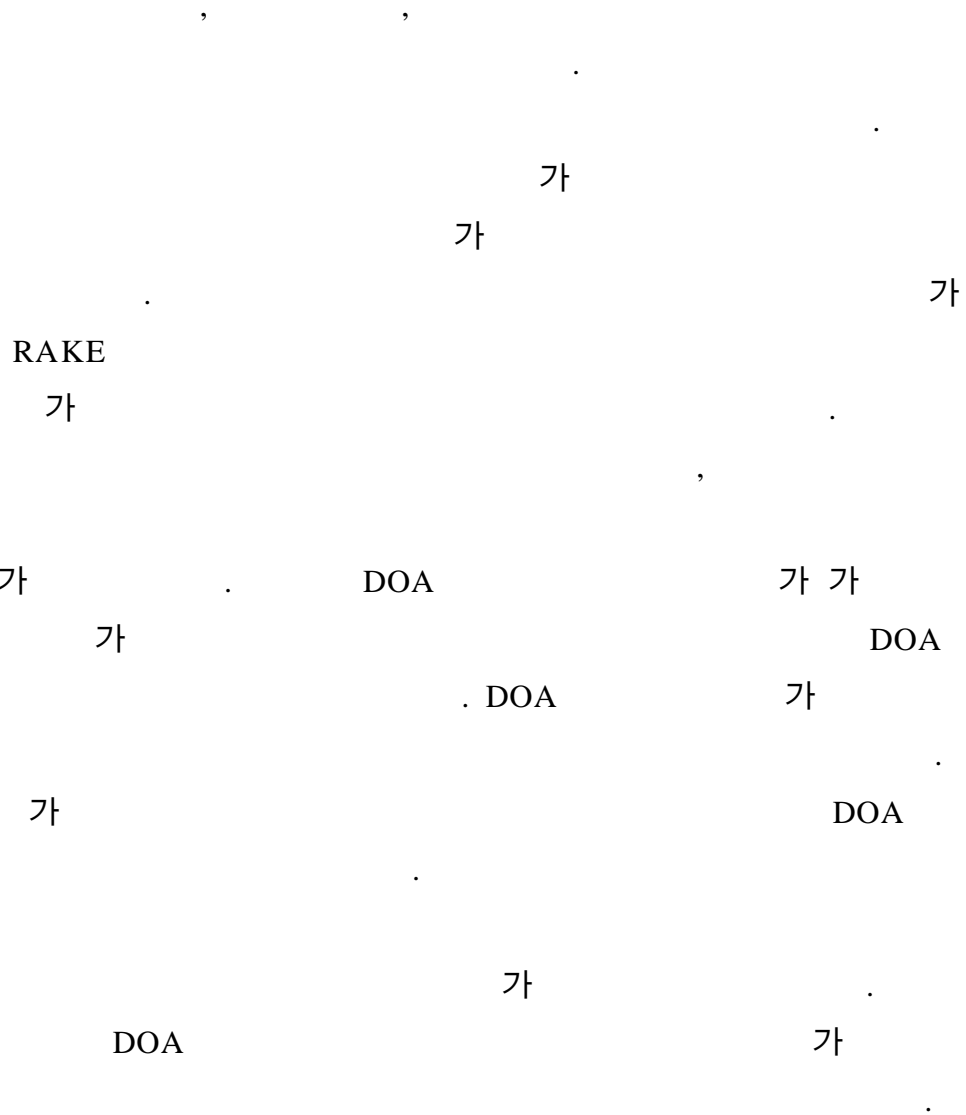
DOA

DOA

가



(3.1) 2



2

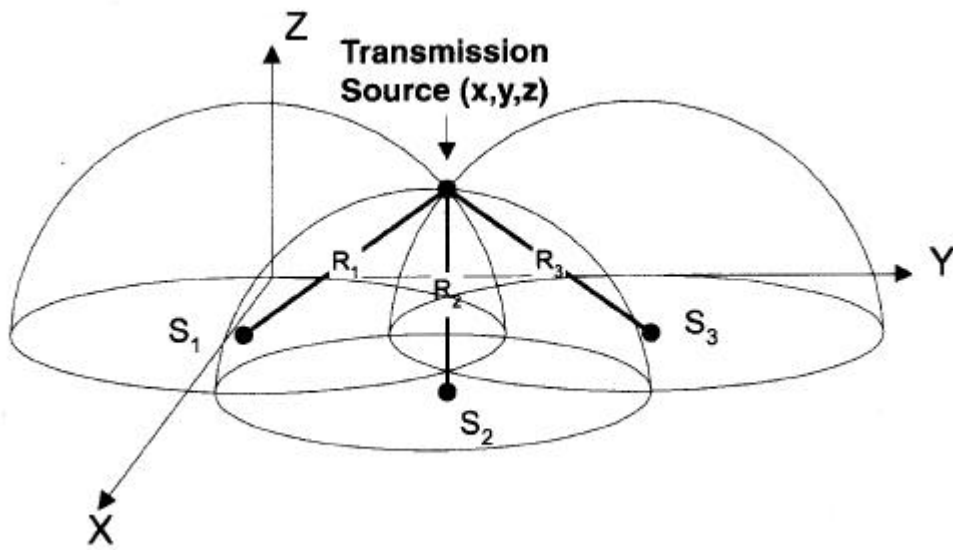
. TOA

가

(3.2)

3

(S_1, S_2, S_3)



(3.2) 3

$$\begin{aligned}
& \text{TOA} \\
& \text{3} \\
& N \\
& R_i = c \tau_i \quad (3.1)
\end{aligned}$$

$$\begin{aligned}
& R_i, c, \tau_i, i \\
& \text{TOA} \\
& N
\end{aligned}$$

$$R_i = \sqrt{(X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2} \quad \text{for } i = 1, 2, \dots, N \quad (3.2)$$

$$\begin{aligned}
& (X_i, Y_i, Z_i) \quad i \\
& R_i \quad i \\
& (x, y, z)
\end{aligned}$$

$$\begin{aligned}
& (3.2) \\
& (N \times 3)
\end{aligned}$$

$$\begin{aligned}
& \text{가} \\
& \text{가}
\end{aligned}$$

GPS
 IS - 95 GPS
 Sync
 가

(TOA)
 가

,
 PCS

가

3

(3.3) 2
 $R_{i,j}$

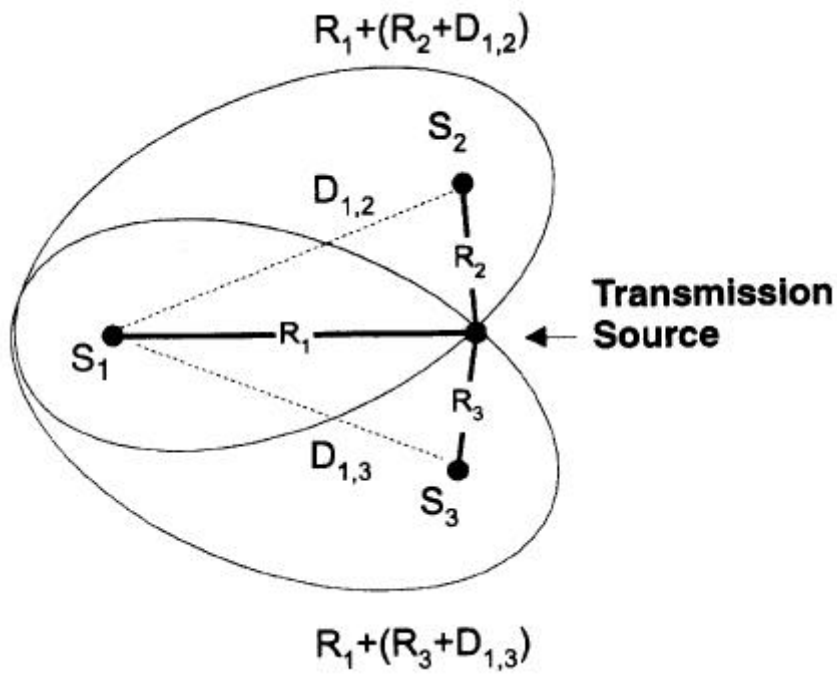
$$R_{i,j} = c\tau_{i,j} = c(\tau_i + \tau_j) = R_i + R_j \tag{3.3}$$

c , $\tau_{i,j}$ i, j TOA
 가

$$R_{i,j} = \sqrt{(X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2} + \sqrt{(X_j - x)^2 + (Y_j - y)^2 + (Z_j - z)^2} \quad (3.4)$$

$$(X_i, Y_i, Z_i) \quad (X_j, Y_j, Z_j) \quad i, j,$$

$$(x, y, z)$$



(3.3) 2

가

가

,

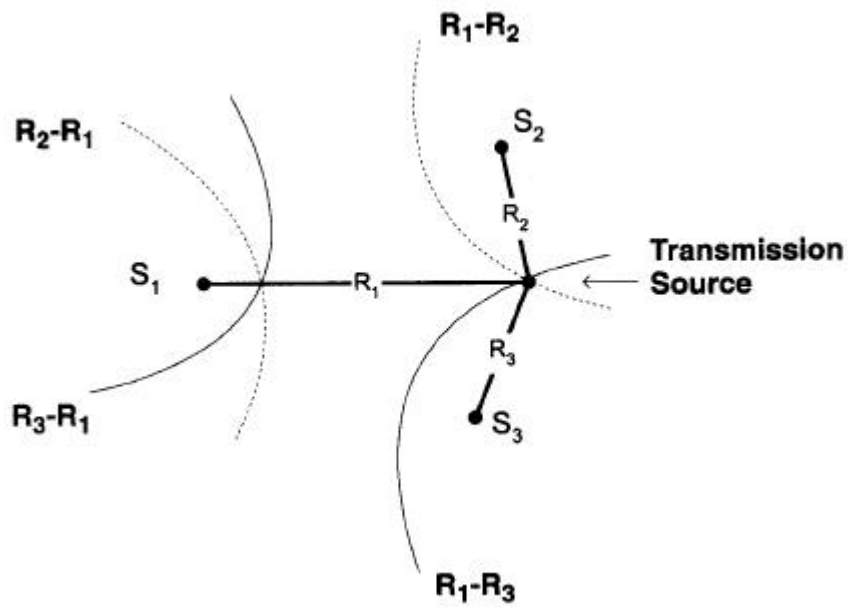
GPS

4

$$R_{i,j} = c \tau_{i,j} = c (\tau_i - \tau_j) = R_i - R_j \quad (3.5)$$

$\tau_{i,j}$ i j

(3.4) 2



(3.4) 2

3

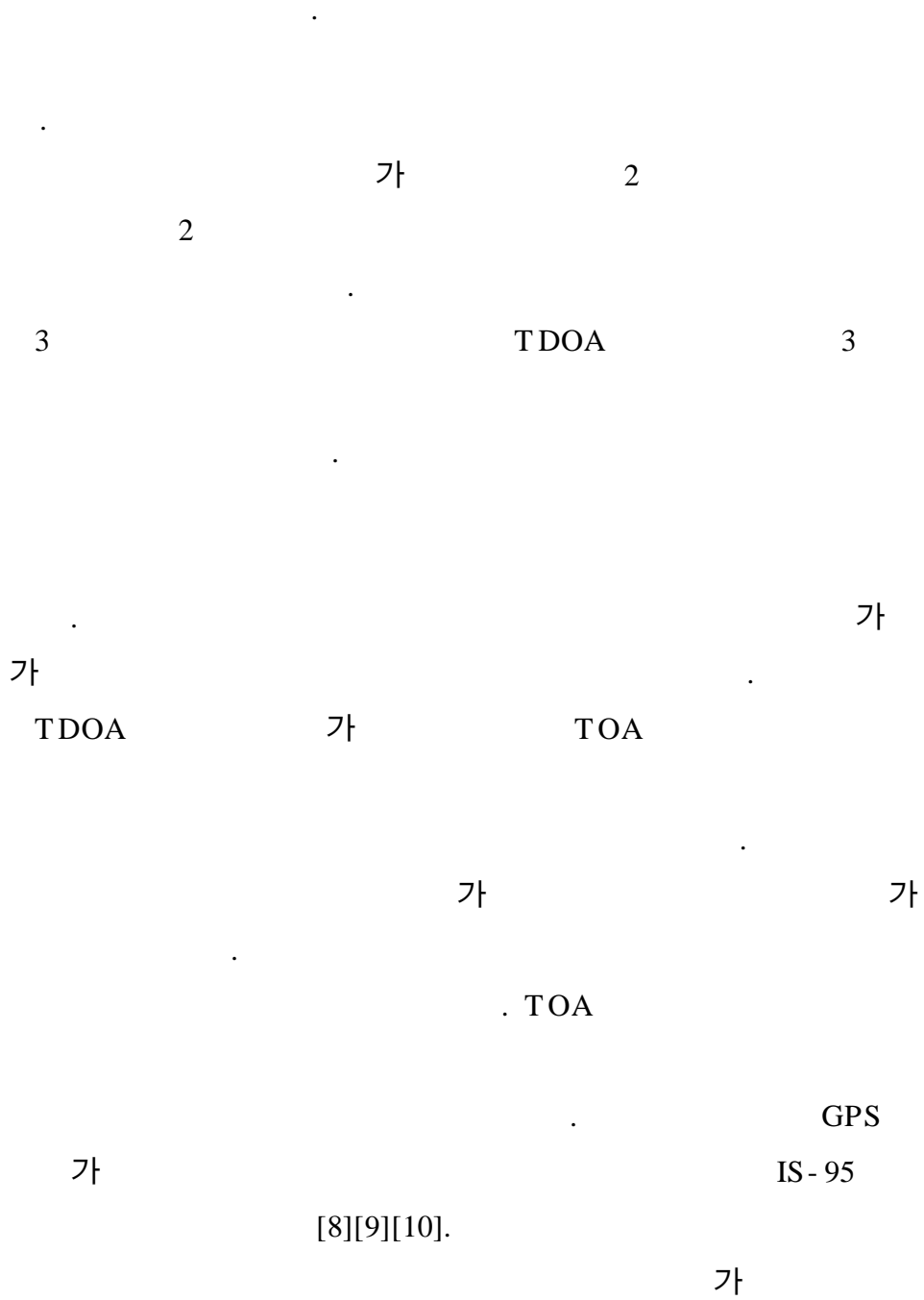
$R_{i,j}$

$$R_{i,j} = \sqrt{(X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2} - \sqrt{(X_j - x)^2 + (Y_j - y)^2 + (Z_j - z)^2} \quad (3.6)$$

$(X_i, Y_i, Z_i) \quad (X_j, Y_j, Z_j) \quad i, j$,

$R_{i,j} \quad i, j$, (x, y, z)

가
가



/ (beam/null steering)

,

.

가

TDOA

가

,

가

.

CDMA

가 가

TDOA

.

CDMA

가

TDOA

.

5 TDOA

가

.

TDOA

.

.

.

(TDOA)

가

TDOA

TOA

,

.

가

,

가

.

,
 .
 ,
 .
 TOA TDOA가
 TOA
 TDOA

1. TDOA

$s(t)$

,
.

$$\begin{aligned}
 x_1(t) &= A_1 s(t - d_1) + n_1(t) \\
 x_2(t) &= A_2 s(t - d_2) + n_2(t)
 \end{aligned}
 \tag{3.7}$$

A_1, A_2 $n_1(t), n_2(t)$
 d_1, d_2 .

$s(t)$ jointly stationary 0
 $n_1(t), n_2(t)$ 가 . 가 가
 $d_1 < d_2$ 가

$$\begin{aligned}
 x_1(t) &= s(t) + n_1(t) \\
 x_2(t) &= A s(t - D) + n_2(t)
 \end{aligned}
 \tag{3.8}$$

$$A \quad s(t) \quad , \quad D = d_2 - d_1$$

$$D \quad .$$

$$A \quad ,$$

$$. \quad \text{가}$$

$$D$$

$$A \quad .$$

$$.$$

$$R_{x_2x_1}^{\alpha}(\tau) = A R_s^{\alpha}(\tau - D)e^{-j\pi\alpha D} + R_{n_2n_1}^{\alpha}(\tau) \quad (3.9)$$

$$R_{x_1}^{\alpha}(\tau) = R_s^{\alpha}(\tau) + R_{n_1}^{\alpha}(\tau) \quad (3.10)$$

$$R_{x_2}^{\alpha}(\tau) = |A|^2 R_s^{\alpha}(\tau)e^{-j\pi\alpha D} + R_{n_2}^{\alpha}(\tau) \quad (3.11)$$

$$\alpha \quad . \quad \alpha = 0$$

$$[11].$$

$$s(t) \text{가 } n_1(t), n_2(t) \quad \alpha$$

$$(3.10) \quad (3.11) \quad \alpha$$

$$.$$

$$R_{n_1}^{\alpha}(\tau) = R_{n_2}^{\alpha}(\tau) = R_{n_2n_1}^{\alpha}(\tau) = 0 \quad (3.12)$$

$$.$$

$$R_{x_2x_1}^{\alpha}(\tau) = A R_s^{\alpha}(\tau - D)e^{-j\pi\alpha D} \quad (3.13)$$

$$R_{x_1}^{\alpha}(\tau) = R_s^{\alpha}(\tau) \quad (3.14)$$

$$R_{x_2}^{\alpha}(\tau) = |A|^2 R_s^{\alpha}(\tau)e^{-j\pi\alpha D} \quad (3.15)$$

D

Generalized cross-correlation (GCC)
cyclostationarity-exploiting cross-correlation
cyclostationarity-exploiting Cyclocross-correlation
(CYCCOR), Spectral-coherence alignment (SPECCOA),
Band-Limited Spectral Correlation Ratio (BL-SPECCORR),
Cyclic Prony.

(Signal Selective) cyclostationarity-exploiting

가 GCC

[11][12]. CDMA

GCC

GCC TDOA.

2. Generalized Cross-correlation

TDOA

Generalized Cross-correlation(GCC). GCC

가

TDOA.

(SNR)가 가

가. TDOA GCC

(3.13) α 0 [5]. (3.13)

$$R_{x_2x_1}^0(\tau) = A R_s^0(\tau - D) \quad (3.16)$$

$$(3.16) \quad \tau \quad \text{TDOA} \quad D$$

$$(3.16)$$

$$R_{x_2x_1}(\tau) = R_{x_2x_1}^0(\tau) = \int_{-\infty}^{\infty} x_1(t)x_2(t-\tau)dt \quad (3.17)$$

$$R_{x_2x_1}(\tau)$$

$$\hat{R}_{x_2x_1}(\tau) = \frac{1}{T} \int_0^T x_1(t)x_2(t-\tau)dt \quad (3.18)$$

$$T$$

$$N$$

$$\hat{R}_{x_2x_1}(m) = \frac{1}{N} \sum_{n=0}^{N-|m|-1} x_1(n)x_2(n+m) \quad (3.19)$$

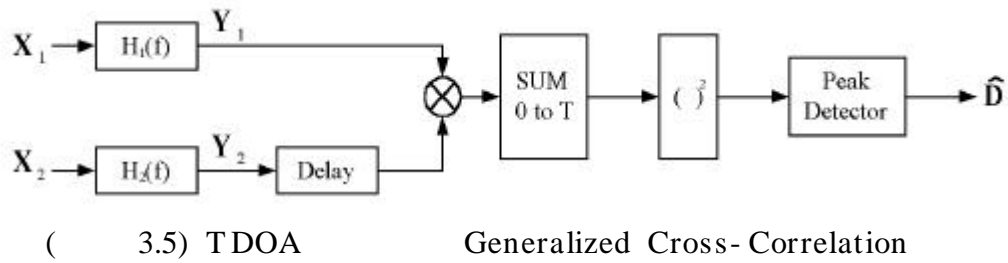
$$(3.18) \quad x_1(t), \quad x_2(t)$$

$$G_{x_2x_1}(f)$$

$$R_{x_2x_1}(\tau) = \int_{-\infty}^{\infty} G_{x_2x_1}(f)e^{j\pi f\tau}df \quad (3.20)$$

$$G_{x_2x_1}(f) = \int_{-\infty}^{\infty} R_{x_2x_1}(\tau)e^{-j\pi f\tau}d\tau \quad (3.21)$$

$$x_1(t) \quad x_2(t) \quad G_{x_2x_1}(f) \quad \hat{G}_{x_2x_1}(f) \quad .$$



$$(3.18)$$

$$. (3.5)$$

$$x_1(t), \quad x_2(t) \quad , \quad , \quad , \quad . \quad \text{TDOA}$$

$$\hat{D} \quad [13]. \quad \text{가} \quad D$$

$$x_1(t), \quad x_2(t) \text{가} \quad ,$$

$$G_{y_2y_1}(f) = H_1(f)H_2^*(f)G_{x_2x_1}(f) \quad (3.22)$$

$$“ * ” \quad . \quad \text{G가}$$

$$x_1(t), \quad x_2(t) \quad \text{Generalized cross-correlation} \quad .$$

$$R^G_{y_2y_1}(\tau) = \int_{-\infty}^{\infty} \Psi_G(f) G_{x_2x_1}(f) e^{j\pi f \tau} df \tag{3.23}$$

$$\Psi_G(f) = H_1(f)H_2^*(f) \tag{3.24}$$

가

$$R^G_{y_2y_1}(\tau) \tag{3.23}$$

$$\widehat{R^G}_{y_2y_1}(\tau) = \int \Psi_G(f) \widehat{G}_{x_2x_1}(f) e^{j\pi f \tau} df \tag{3.25}$$

D . GCC

$$\Psi_G(f)$$

$\Psi_G(f)$

가

D

$$H_1(f) = H_2(f) = 1$$

$$\Psi_G(f) = 1, \quad \widehat{G}$$

$$(\quad 3.1)$$

(3.1) GCC

Processor Name	Frequency Function $\Psi_G(f)$
Cross- Correlation	1
Roth Impulse Response	$1/G_{x_1x_1}(f)$ or $1/G_{x_1x_1}(f)$
Smoothed Coherence Transform	$1/\sqrt{G_{x_1x_1}(f)G_{x_2x_2}(f)}$
Eckart	$G_{s_1s_1}(f)/(G_{n_1n_1}(f)[G_{x_2x_2}(f)])$
Hannon- Thomson or Maximum Likelihood	$\frac{ \gamma_{x_1x_2}(f) ^2}{ G_{x_1x_1}(f) [1- \gamma_{x_1x_2}(f) ^2]}$

GCC

가 ,

가 ,

(overlapping) TDOA

. $s(t)$, $n_1(t)$, $n_2(t)$ 가

가

GCC

.

GCC

(Signal

selective)

TDOA

.[12].

IS-95 W-CDMA RAKE

TDOA

3.

. TDOA ,
 가 TDOA
 1
 Carter
 [14].
 가
 . Hahn 가
 가 TDOA
 가
 가
 가 [13][15].
 Abel and Smith Carmér-Rao Lower
 Bound(CRLB)
 . CRLB TDOA
 (
)
 TDOA

(3.6)

가
가

가

(3.6)

Taylor Series

가

가

가

3 6 3. GDOP (Geometric Dilution of Precision)

Bancroft

2

GDOP

Nicholson

[17][18].

(Least Square : LS) 가

(Weighted Least-Square

: WLS) .

가 Maximum Likelihood (ML)

가 가 0

가 가 LS ML

[13]. 가 WLS ML .

WLS 가 .

.

가 가

Fang

[20]. TDOA

Spherical-Intersection (SX) , Spherical-Interpolation(SI) , Divide and Conquer (DAC) , Chan , Taylor Series . Taylor Series

TDOA

가

.

.

4.

M 2

TDOA

가 가

.

(x, y) , (X_i, Y_i) i

$$, \quad (3.2) \quad i$$

.

$$\begin{aligned} R_i(x, y) &= \sqrt{(X_i - x)^2 + (Y_i - y)^2} \\ &= \sqrt{X_i^2 + Y_i^2 - 2X_i x - 2Y_i y + x^2 + y^2} \end{aligned} \quad (3.26)$$

(3.26)

.

$$\begin{aligned} R_{i,1}(x, y) &= c\tau_{i,1} = R_i(x, y) - R_1(x, y) \\ &= \sqrt{(X_i - x)^2 + (Y_i - y)^2} - \sqrt{(X_1 - x)^2 + (Y_1 - y)^2} \end{aligned} \quad (3.27)$$

$$c, \quad R_{i,1} \quad i$$

$$R_1$$

$$, \quad \tau_{i,1} \quad i$$

TDOA . 2

. (3.26), (3.27)

$$2 \quad (x, y)$$

.

$$(x, y)$$

.

Taylor

Series

Taylor Series (3.27) TDOA 1

.

$$\begin{aligned}
R_{i,1}(x, y) &= R_{i,1}(x_v + \delta x, y_v + \delta y) \\
&\approx R_{i,1}(x_v, y_v) - \left(\delta x \frac{\partial}{\partial x} + \delta y \frac{\partial}{\partial y} \right) R_{i,1}(x, y) |_{x=x_v, y=y_v} \\
&\approx R_{i,1}(x_v, y_v) + \delta x \left[\frac{(X_i - x_v)}{R_i(x_v, y_v)} - \frac{(X_1 - x_v)}{R_1(x_v, y_v)} \right] \\
&\quad + \delta y \left[\frac{(Y_i - y_v)}{R_i(x_v, y_v)} - \frac{(Y_1 - y_v)}{R_1(x_v, y_v)} \right] \\
&\quad (x, y) \quad .
\end{aligned} \tag{3.28}$$

가 (x_v, y_v) , Tylor Series

.

.

$$\begin{aligned}
x &= x_v + \delta x \\
y &= y_v + \delta y
\end{aligned} \tag{3.29}$$

TDOA

$e_{i,1}$

.

$\delta x, \delta y$

.

$$\begin{aligned}
&\left[\frac{(X_i - x_v)}{R_i(x_v, y_v)} - \frac{(X_1 - x_v)}{R_1(x_v, y_v)} \right] \delta x + \left[\frac{(Y_i - y_v)}{R_i(x_v, y_v)} - \frac{(Y_1 - y_v)}{R_1(x_v, y_v)} \right] \delta y \\
&\approx R_{i,1}(x, y) - (R_i(x_v, y_v) - R_1(x_v, y_v)) - e_{i,1}
\end{aligned} \tag{3.30}$$

(x_v, y_v)

$\{e_{i,1}\}$

TDOA

(x_v, y_v)

$\delta x, \delta y$

.

$\delta x, \delta y$ 가

.

Abel[21] Devide and Conquer(DAC) , TDOA

· ,

·

Fisher

· Fisher Information Matrix (FIM) Cramèr- Rao Matrix
Bound (CRMB) [15].

Chan

(Closed- form)

가 TDOA 가

Maximal Likelihood(ML) .

Spherical- Intersection (SX) Spherical- Interpolation (SI)

LS (Rapid convergence) .

·

가

· Taylor Series LS

,

가 가 .

Fang

·

Friedlander [17]

SI SX 가 가 .

·

Chan (closed form)

가 , TDOA 가 , 가 ,

6

가 . 가
 Cramèr-Rao Lower Bound (CRLB)
 (MSE)
 가
 Circular Error Probability (CEP :)
 .
 GDOP(Geometric Dilution of Precision)
 GDOP CEP 가 .

1. MSE Cramèr- Rao Lower Bound

(x, y) Cramèr- Rao
 Lowerx Bound
 . 2 MSE
 .

$$\text{MSE} = \varepsilon = E[(x - x_v)^2 + (y - y_v)^2] \quad (3.31)$$

$$(x, y), (x_v, y_v)$$

Root-Mean Square Error (MSE)

$$\text{RMS Error} = \sqrt{\varepsilon} = \sqrt{E[(x - x_v)^2 + (y - y_v)^2]} \quad (3.32)$$

MSE, RMS, Cramér-Rao Lower Bound (CRLB)

Cramér-Rao Lower Bound (CRLB)

Stationary 가

Stationary 가

CRLB [24].

$$\text{TDOA}_{\text{rms}} = (2\pi f \sqrt{2b\tau} \cdot \text{RSNR})^{-1} \quad (3.33)$$

TDOA_{rms}

rms, RSNR(Raw-Signal-to-Noise-Ratio)

$$\text{RSNR} = \frac{\sqrt{\text{SNR}_1 \text{SNR}_2}}{\sqrt{1 + \text{SNR}_1 + \text{SNR}_2}} \quad (3.34)$$

$$\text{SNR}_i, i = 1, 2$$

$$(\text{dB}), \quad (3.33) \quad \tau$$

$$(\text{Hz}), b \quad (\text{Hz}), f$$

rms RF (Hz)

(3.33) TDOA

가
가
가
GDOP 가

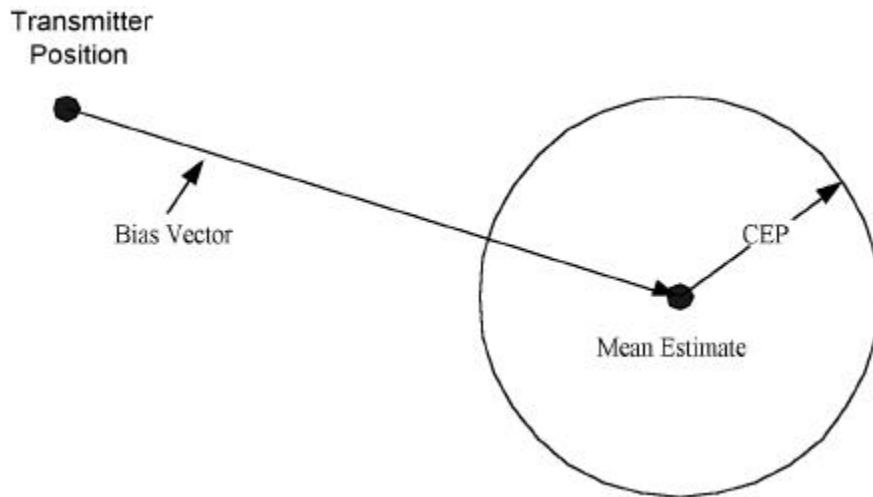
2. Circular Error Probability (CEP:)

(CEP) CEP 가
[25]. 2 CEP 가
CEP 가

B
B+CEP(Bias + CEP) . (3.6)
CEP
CEP 10%

$$CEP \approx 0.75 \sqrt{\sigma_x^2 + \sigma_y^2} \quad (3.35)$$

σ_x^2, σ_y^2 x, y



(3.6)

3. Geometric Dilution of Precision

. TDOA

Geometric Dilution of Precision(GDOP) [20]. GDOP
RMS RMS

GDOP

$$GDOP = \sqrt{tr[(A^T A)^{-1}]} \quad (3.36)$$

$tr(\bullet)$ (trace)

$A = E[u(t) u^H(t)], y(t)$ M- dimensional M

. 2

GDOP

$$\begin{aligned} \text{GDOP} &= (\sqrt{(c\sigma_x)^2 + (c\sigma_y)^2}) / \sqrt{(c\sigma_s)^2} \\ &= (\sqrt{\sigma_x^2 + \sigma_y^2}) / \sigma_s \end{aligned} \quad (3.37)$$

$$(c\sigma_s)^2 = (c\sigma_x)^2 + (c\sigma_y)^2 \quad x, y$$

y

GDOP TDOA

가

. CEP

GDOP

$$\text{CEP} = (0.75 \sigma_s) \text{GDOP} \quad (3.38)$$

GDOP

. GDOP

4.

, 가 (NLOS :

Non Line-of-Sight) ,

가.

AOA

가 (LOS : Line-of-Sight)

가

가

가

[29] LMS [30]

가

Root-MUSIC TLS-ESPRIT

. Extended Kalman

Filter(EKF)

가 [31]

. 가

NLOS

, 가 . NLOS

, TOA TDOA

NLOS

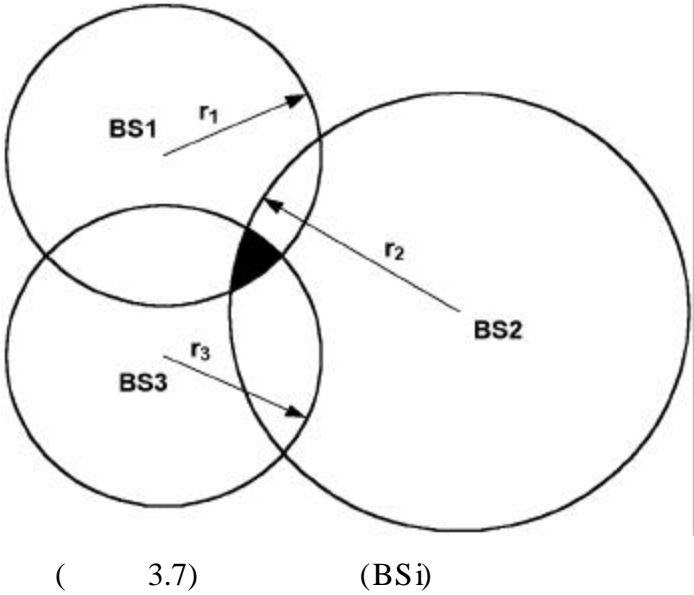
. TOA

LOS NLOS

LOS NLOS .[32]

, LOS NLOS

. LS NLOS 가
 . , NLOS
 가
 .
 NLOS가 TOA TOA
 가
 N $r_i = c(\tau_i - \tau)$,
 $i = 1, \dots, N$



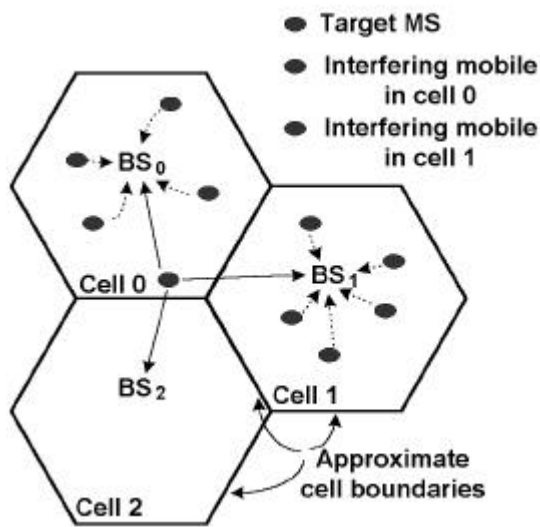
LS
 .

$$r_i = c(\tau_i - \tau) \geq \sqrt{(x_i - x)^2 + (y_i - y)^2} \tag{3.39}$$

(x, y) 가
 (3.39) NLOS
 가
 가
 NLOS 가

(Multiple Access Interference)
 . CDMA

가 DLL
 가
 가



(3.8) CDMA
(Near- Far Effect)

CDMA

(Near- far effect)

.
(3.8) .
. BS_0, BS_1, BS_2 가
, BS_0 .
, BS_0 (
) 가 BS_0 . BS_1 (
) BS_2 (
) BS_1 BS_2
. 가
, BS_1 BS_2 BS_1
 BS_2

. TOA TDOA
 . 가 E-911
 . 가
 . 가
 .

4

1

GPS

DGPS

GPS

/

가

가

GPS

가 .

[28][33].

1. AMPS/USDC

AMPS(Advanced

Mobile Phone Sytem)

1982

가

가

AMPS

AMPS

AMPS USDC(US Digital Cellular)

가

AMPS

USDC

AMPS

AMPS

가

10 μ s

AMPS

Associated Group True Position, True Position

TDOA True Position

, 4

SCS(Signal Collection System),

TLP(TDOA Location Processor), AP(Application Processor),

NOC(Network Operations Center)

SCS 21

time-stamped segment

SCS

가

가

ID

가

SCS

TLP

TLP

TOA ,

.

Doppler shift .

, , AP

.

TLP (MSC)

AP TLP

, NOC . 1997

180 m

가 .

FCC Phase II

Allen Telecom Grayson Wireless , Allen Telecom

1996 Signal Science Inc. 1997 Raytheon E-System

Geometrix True Position

. Geometrix

(location sensor)

. Allen

Telecom 가

. 가 2

4 TDOA .

가 .

, AOA TDOA

가 . 가 가 AOA TDOA

.

가 (가
) AOA
 . CAPITAL AMPS
 TDOA AOA .[]
 108 m
 .

2. CDMA

CDMA

가

가 .
 CDMA
 가 CDMA TDOA
 가 가 . ,
 . , TDOA 가
 (Power Control)
 가
 .

. TDOA

.

Near- Far

가 .

가. IS - 95

IS - 95

TDOA

가

. IS - 95

(1.25 MHz)

가

. IS - 95

[29].

3

가

가 (hearability)

, IS - 95

가 short burst

Power-Up Function 가 .

Power Up Function(PUF) FCC E- 911

IS- 95B

.

IS - 95

CDMA

3

가

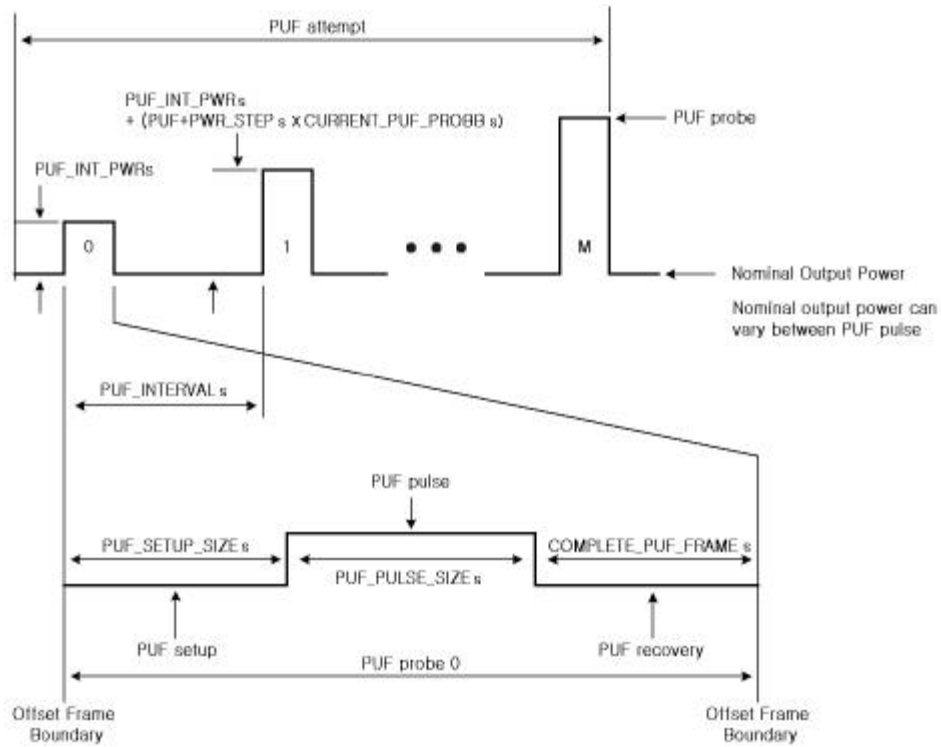
Near - Far

. Power Up Function

가

hearability

. IS- 95B PUF attempt (4.1) [28].



(4.1) PUF Attempt

. IS - 95

IS - 95

PN

PN

IS - 95

가 . PMRO(pilot measurement request order)

,

PN
가 PN serving
, IS-95
TDOA
가 3 3
,

PN
, , 가 . IS-95
3 μs

IS-95 GPS
nsec
가

1997 IS-95
IS-95 3

. FCC Phase II
가

가

pilot pollution

가

pilot pollution

trade-off가

3. GSM

GSM(Global System for Mobile Communications) GSM

DCS 1800, PCS 1900 가

. GSM

. GSM 200

kHz AMPS IS-136

TOA TDOA

가 . GSM

가

GSM

TIA(Telecommunications

Industry Association) T1

ETSI (European Telecommu-

nications Standards Institute)

. 3

GSM (Location
Services : LCS) TA(Timing
Advance) 3가 .

GPS

- TOA

- E-OTD(Enhanced Observed Time Difference) :

Mobile Assisted, Mobile Based

- Assisted GPS : Network Assisted, Network Based

가. OTD

(4.2) GSM

가

. OTD(Observation of Time
Difference) ,

.

가

OTD가

RTD(Real Time Difference) ,

가

.

.

.

가

RTD

.

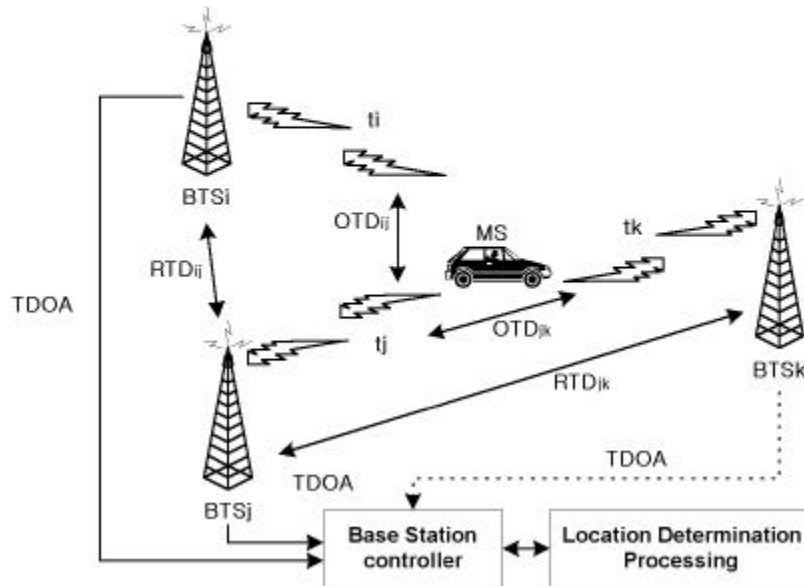
GSM

,

GSM

.

- * t : propagation time
- * OTD : Observed Time Difference between signals from BTSs
- * RTD : Actual Relative Time Difference between clocks from BTSs
- * TDOA : Time Difference Of Arrival



(4.2) OTD

. TA

advance

GSM

GSM

advance

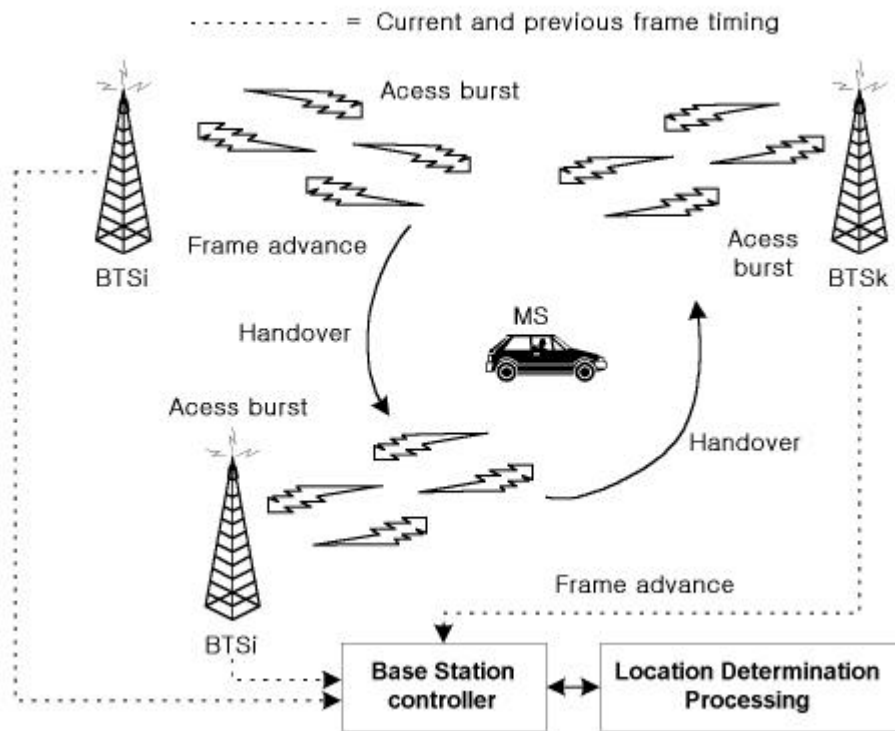
advance

가 . 가

. (4.3)

TA

GSM



(4.3) TA

• TOA

TOA

(

)

TOA

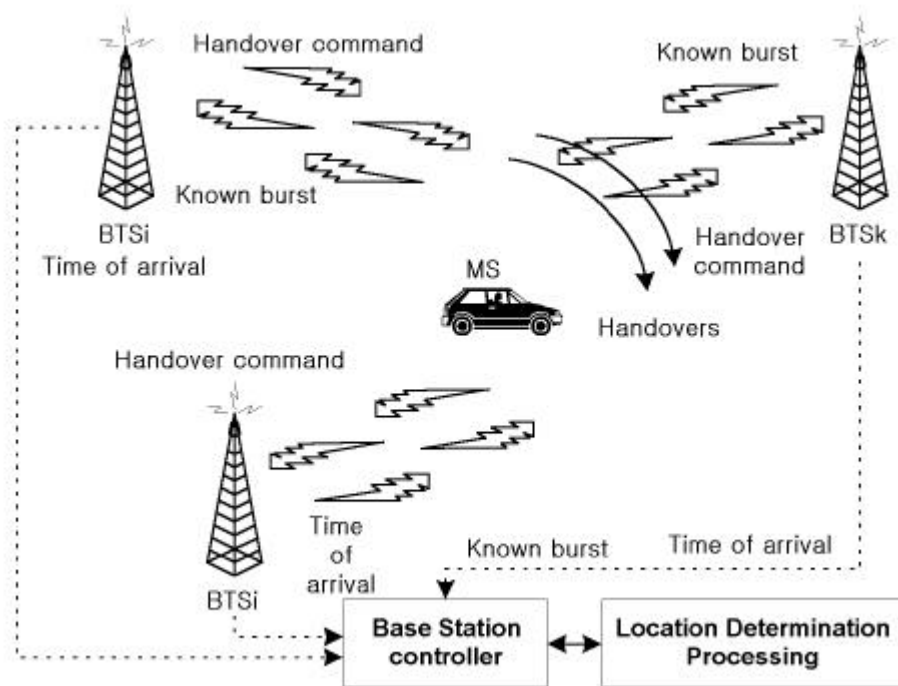
가

TOA가

가

DSP

(4.4)



(4.4) TOA

2

가

-

-

(,)

.

1.

가

.

.

(SIR : Signal to Interference ratio) E_b/N_0

.

.

.

.

FCC

(rms:

root mean square)

가

FCC

.

.

가

, , ,

.

FCC E-911

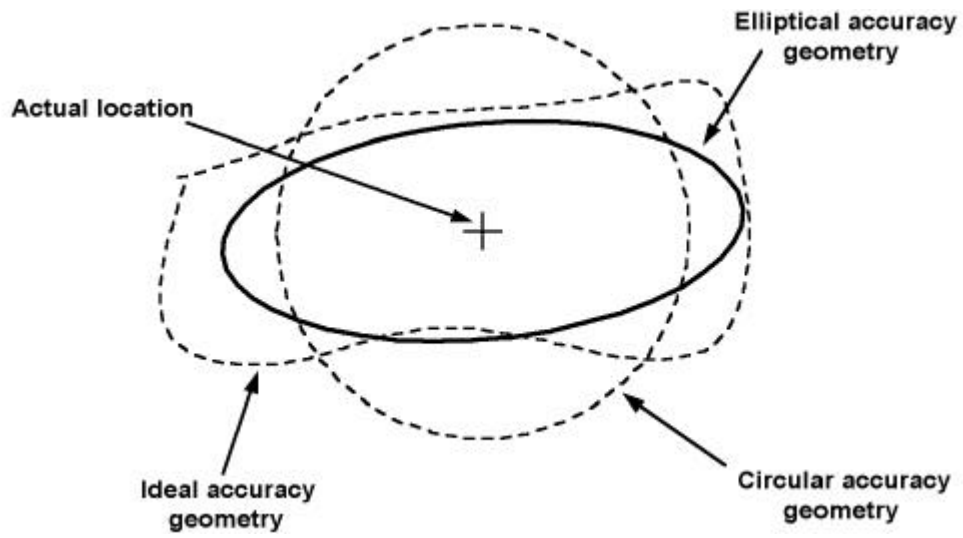
125 m

67 %

.

(4.5)

가



(4.5)

()

가

GDOP(Geometric dilution of precision)

GDOP

가

[9].

, 가 .
 . (4.1)
가 .
, , , , 6 가
 . 67 %가
 .
가 - .

(4.1) 가

		(m) (67%)
	20 %	500
	30 %	100
	30 %	60
	10 %	80
	10 %	80
= 가		= 164 m

. E- 911

911

가 .

. FCC Phase 2

.
.

2. (Blocking Rate)

가 .

.
가 가 .
“Missed call” ()

(
) . 가 가
. “Missed call”

. “Missed call”

“ ”

. FCC Phase 1

가

Phase 2

가 (MTBF:Mean Time Between Failures)
가 (MTTR: Mean Time to Repair)

(4.2)

(4.2)

<ul style="list-style-type: none"> - E_b/N_0 , , 	<ul style="list-style-type: none"> -
<ul style="list-style-type: none"> - (,) - 가 	<ul style="list-style-type: none"> - "Missed call"(, ,) -
<ul style="list-style-type: none"> - (Busy Hour Call Attempts), Erlangs, 가 	<ul style="list-style-type: none"> - /
<ul style="list-style-type: none"> - (,) - (MTBF,MTR) - lookup - - 	<ul style="list-style-type: none"> - (, ,) - (MTBF, MTTR) - lookup - - -

3

E-911 가
3
IMT-2000
가 IMT-2000
IMT-2000
가 3GPP
3GPP ETSI SMG
.

1.

가. FCC
911 1968
. E-911 1996
(FCC) First Report and Order CC Docket No. 94-102
911
. PCS SMR 1997
10 911 가
(MIN: Mobile Identification Number) PSAP(Public
Safety Answering Point)
1998 4 1 E-911 Phase I

. E- 911 Phase I 911
 PSAP . E- 911
 911 가 , LEC
 , LEC 911 PSAP
 . 90%
 911 . 2001 10 1
 Phase II 911
 67% 100 m 가
 PSAP .
 (ANI: Automatic Number Identification)
 (ALI : Automatic Location Identification) 911
 가 가 PSAP
 가 .
 911 가
 . NENA(National
 Emergency Numbering Association) 911
 85% 가 911 E- 911
 가 .
 가 (further Notice of
 Proposed Rulemaking) 1999 6 Second Report and Order
 A/B - , /가 ,
 .

. T1 ETSI

T1 T1P1 (Location
Service : LCS)

ETSI(European Telecommunications Standards Institute)

SMG(Special Mobile Group)

GSM PCS1900 , 3

. 1

, 2 , 3

. 1 , 2

99 4/4 . 2 1

TOA OTD GPS

가 . 3 1, 2 가

1, 2

1

가

, MMI(Man Machine

Interface)

.

● Allen Telecom

Allen Telecom Geometrix

. Allen Telecom 99 2 IS- 95

(trial service)

Geometrix

FCC 125 m

, AMPS, TDMA(IS- 136),

CDMA(IS-95)

.

- Cambridge Positioning Systems

CPS CURSOR GSM

. EOTD(Enhanced Observed Time Difference)

1999

.

MX-3204 GSM

Maxon

.

- Harris Corporation

MicroTrax

. 902 908 MHz ISM

, TDOA AOA

.

- IDC(Integrated Data Communications)

GPS

solution

. GPS

. IDC GPS 가

가 PSAP

.

- KSI, Inc.

KSI (, PCS, SMR)

DFLS(Direction Finding Location System)

RF

RF

FCC 125 m

Central Land Station(CLS)

KSI DFLS

- SigmaOne

SigmaOne AOA TDOA

, 1998 5 E-911

345 ft(105 m)

SigmaOne AMPS, TDMA(IS-136), CDMA(IS-95),
GSM(J-STD-008) LA
San Fernando Valley, TDMA

- SnapTrack

EGPS(Enhanced GPS) GPS

DSP

6

7 CDMA (AirTouch Comm., Ameritech
Cellular, Bell Mobility, GTE Wireless, PrimeCo Personal Comm.,
Sprint PCS, US West), 2 (LSI Technology, TI)
SnapTrack CDMA Testing Group(STCTG) CdmaOne

EGPS 1998 8
 “City and Country of Denver” ”Adams Country Communications
 ADCOM 9- 1- 1" 가
 FCC Phase II . (

4.3) California San Francisco San Jose, Colorado
 Denver Boulder .

(4.3) STCTG (: SnapTrack, 1998)

	<=125 m (%)	67 % (m)	98 % (m)
	100	10	20
	100	40	80
	95	30	60
	0- 100	55	110
	98	90	180

5 Florida Tampa

- Tendler Cellular

1998 7 FoneFinder . GPS
 911 GPS

FoneFinder EMS .

- TruePosition

Associated Group 가
TV Associated Communications
Corporation .

TruePosition

TDOA

TruePosition Release 1 AMPS N- AMPS .

TDMA/AMPS CDMA/AMPS

.

500 feet 90% 가 .

가 가 .

Associated Group

.

TruePosition TDOA 가

.

99 2 Trueposition Corsair
, Corsair PhoneTrack

.

- US Wireless

US Wireless 1996

.

Location Fingerprinting(LF)

RadioCamera

. RadioCamera RF

(, , ,)
 RF RF “fingerprint”
 . TDOA TOA

RadioCamera
 10 m RF
 . RF fingerprint
 RF
 . RadioCamera

(4.4)

		/	
Allen Telecom	Geometrix	- AOA+TDOA	AMPS
Cambridge Positioning System (CPS)	Cursor	- GSM ,	GSM
Corsair Communications	PhoneTrack	AOA+TDOA	AMPS
Harris Corporation		- AOA+TDOA	
Integrated Data Communication (IDC)		- GPS	
KSI		- AOA	AMPS, TDMA
SigmaOne		- AOA+TDOA	AMPS
SnapTrack		- GPS	AMPS
Tendler Cellular	FoneFinder	- - GPS	AMPS
TruePosition		TDOA	AMPS
US wireless	RadioCamera	-	AMPS

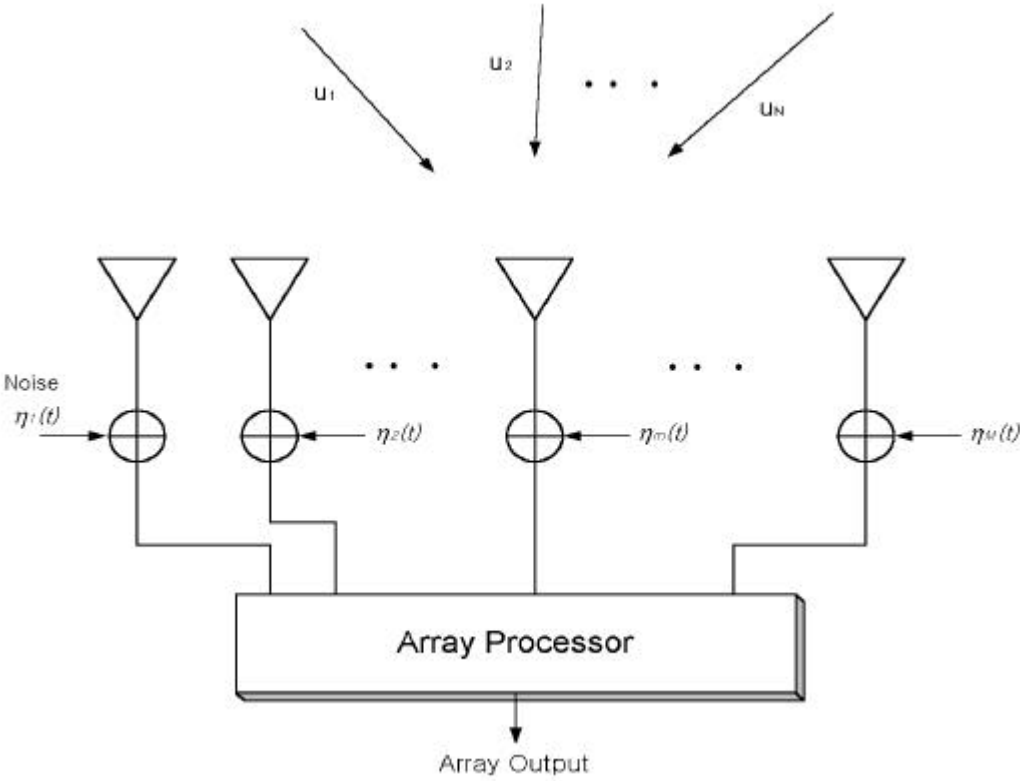
5

1940
가, 1970
Capon[34][35] Maximun Likelihood Method (MLM)
Linear Prediction Method (LPM ;) [36][37][38],
1980
[39][40][41][42].

1

- . (5.1)
- 가 .
- (1) . (0)
- (2) ()
 ω_0 c .
- (3) 가
 R_η . ()
가 가 .)

(4) 가 0 W.S.S.
(Wide- Sence Stationary) 0
가 .



(5.1)

가

3

$\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3, \cdots, \mathbf{r}_M$

$$\mathbf{u}_1, \mathbf{u}_2, \mathbf{u}_3, \cdots, \mathbf{u}_N \quad N \quad \text{가}$$

$$\text{가} \quad \mathbf{u}_n \quad (1 \leq n \leq N) \quad m \quad (1 \leq m \leq M)$$

$$\mathbf{r}_m \quad .$$

$$\tau_n(m) = \frac{\mathbf{r}_m \cdot \mathbf{u}_n}{c} \quad (5.2)$$

$$\begin{aligned} & \omega_0 && (2\pi f_0), \, c \\ & , \, \phi_n && n && , \, g_n(t) && n \\ & , \, \eta_m(t) && m && \text{가} && , \, \mathbf{r}_m && m \\ & , \, \mathbf{u}_n && n && && , \, \mathbf{r}_m \cdot \mathbf{u}_n && \mathbf{r}_m \\ & . \, \phi, \, \theta && && && . \end{aligned}$$

$$\mathbf{x}(t) = [x_1(t), x_2(t), \dots, x_M(t)]^T \quad \mathbf{C}^M$$

$$S = [s_1, s_2, \dots, s_N] \in \mathbb{C}^{M \times N}$$

$$\mathbf{s}_n = [e^{j\omega_0 \tau_n(1)}, e^{j\omega_0 \tau_n(2)}, \dots, e^{j\omega_0 \tau_n(M)}]^T \quad C^M$$

$$\mathbf{g}(t) = [g_1(t)e^{j\omega_1 t}, g_2(t)e^{j\omega_2 t}, \dots, g_N(t)e^{j\omega_N t}]^T \in \mathbb{C}^N$$

$$\boldsymbol{\eta}(t) = [\eta_1(t), \eta_2(t), \dots, \eta_M(t)]^T \in \mathbb{C}^M$$

$$\mathbf{S} \in \mathbb{C}^{M \times N} \quad \mathbf{s}_n$$

$$\mathbf{S} \in \mathbb{C}^{M \times M}$$

$$\mathbf{R} = E[\mathbf{x}(t) \mathbf{x}^*(t)] \quad (5.5)$$

$$E[\mathbf{x}(t) \mathbf{x}^*(t)] = \mathbf{R} \quad (5.4) \quad (5.5)$$

$$\mathbf{R} = \mathbf{S} \mathbf{R}_g \mathbf{S}^* + \sigma_\eta^2 \mathbf{R}_\eta \quad (5.6)$$

$$\mathbf{R}_g = E[\mathbf{g}(t) \mathbf{g}^*(t)] \quad (5.7)$$

$$\sigma_\eta^2 \mathbf{R}_\eta = E[\boldsymbol{\eta}(t) \boldsymbol{\eta}^*(t)] \quad (5.8)$$

$$(5.7) \quad \mathbf{R} = \mathbf{S} \mathbf{R}_g \mathbf{S}^* + \sigma_\eta^2 \mathbf{R}_\eta$$

$$(1) \quad \mathbf{R}_g \text{ (nonsingular)}$$

$$\text{(diagonal)}$$

$$(2) \quad \text{가} \quad \mathbf{R}_g$$

$$\text{(nondiagonal)}$$

$$(3) \quad \mathbf{R}_g \text{ (nondiagonal)}$$

$$(5.8) \quad \eta(t) \text{가}$$

$$0 \quad \mathbf{R}_\eta \quad .$$

2

가 가 .

steering vector
steering vector [40].

$$y(t) = \sum_m \alpha_m x_m(t - \tau_m) \tag{5.9}$$

$$(5.9) \quad \tau_m \text{가} \tag{5.2} \quad \frac{\mathbf{r}_m \cdot \mathbf{u}_n}{c} \quad ,$$

$$x(t) \quad s(t) \quad ,$$

$$s(t) \quad \eta_m$$

가 .

$$x_m(t - \tau_m) = s(t) + \eta_m(t - \tau_m) \tag{5.10}$$

$$(5.9) \quad \alpha_m \quad 1 \tag{5.9}$$

.

$$y(t) = Ms(t) + \sum_m \eta_m(t - \tau_m) \tag{5.11}$$

$$\mathbf{M} \quad . \quad y(t) \tag{5.11}$$

M2 가

M 가

$$y(t) \qquad \qquad \qquad \tau_m$$

$$\begin{aligned} & , \\ & \cdot \quad , \\ & . \end{aligned}$$

$$y(\mathbf{k}) = \mathbf{a}^* \mathbf{x} \tag{5.12}$$

$$\mathbf{M} \qquad \mathbf{a}_m$$

$$a_m = c_m e^{j\frac{2\pi}{\lambda} \mathbf{z}_m \cdot \mathbf{k}_0} \tag{5.13}$$

$$,$$

$$\begin{aligned} P(\mathbf{k}) &= E[|y(\mathbf{k})|^2] = E[|\mathbf{a}^* \mathbf{x}|^2] = E[\mathbf{a}^* \mathbf{x} \mathbf{x}^* \mathbf{a}] \\ &= \mathbf{a}^* \mathbf{R} \mathbf{a} \end{aligned} \tag{5.14}$$

$$\mathbf{R} \qquad \qquad \qquad (\text{covariance matrix}), \quad E[\mathbf{X} \mathbf{X}^*]$$

$$, \quad c_m = 1$$

Bartlett

$$\mathbf{P}_{\text{BART}}(\mathbf{k}) = \mathbf{s}^* \mathbf{R} \mathbf{s} \tag{5.15}$$

$$\underline{\mathbf{s}} \quad \text{steering vector} \quad .$$

Bartlett 가

$$\mathbf{k}_0 \quad .$$

$$P_{BART}(\mathbf{k}_0) = M^2 \sigma_s^2 + M \sigma_\eta^2 \quad (5.16)$$

$$(5.16) \quad \sigma_s^2 \quad \sigma_\eta^2 \quad .$$

$$M^2 \quad , \quad M$$

$$M \quad \text{가} \quad .$$

3 Maximum Likelihood Method

Capon[34] Maximum Likelihood method (MLM)

$$\mathbf{w}^* \mathbf{s} = 1 \quad \text{가}$$

$$\mathbf{w} \quad .$$

Lagrange multiplier
[43].

$$F = \mathbf{w}^* \mathbf{R} \mathbf{w} + \alpha (\mathbf{w}^* \mathbf{s} - 1) \quad (5.17)$$

$$\mathbf{w} \quad , \quad \mathbf{s}$$

.

$$(5.17) \quad \text{cost function } F \quad \mathbf{w} \quad F$$

gradient 0' .

$$\nabla F = -2\mathbf{R}\mathbf{w} + \alpha\mathbf{s} = 0 \quad (5.18)$$

$$\mathbf{w} = -\frac{\alpha}{2}\mathbf{R}^{-1}\mathbf{s} \quad (5.19)$$

$$\mathbf{w}^* \mathbf{s} = 1 \quad .$$

$$\mathbf{w}^* \mathbf{s} = \left(-\frac{\alpha}{2}\mathbf{R}^{-1}\mathbf{s}\right)^* \mathbf{s} = -\frac{\alpha}{2}\mathbf{s}^* (\mathbf{R}^{-1})^* \mathbf{s} = 1 \quad (5.20)$$

$$\alpha = \frac{-2}{\mathbf{s}^* \mathbf{R}^{-1} \mathbf{s}} \quad (5.21)$$

$$\mathbf{w} \quad .$$

$$\mathbf{w} = -\frac{1}{2} \cdot \frac{-2}{\mathbf{s}^* \mathbf{R}^{-1} \mathbf{s}} \cdot \mathbf{R}^{-1} \mathbf{s} = \frac{\mathbf{R}^{-1} \mathbf{s}}{\mathbf{s}^* \mathbf{R}^{-1} \mathbf{s}} \quad (5.22)$$

$$\mathbf{u} \quad .$$

$$\begin{aligned} P(\mathbf{u}) &= \mathbf{w}^* \mathbf{R} \mathbf{w} \\ &= \frac{\mathbf{s}^* \mathbf{R}^{-1}}{\mathbf{s}^* \mathbf{R}^{-1} \mathbf{s}} \cdot \mathbf{R} \cdot \frac{\mathbf{R}^{-1} \mathbf{s}}{\mathbf{s}^* \mathbf{R}^{-1} \mathbf{s}} \\ &= \frac{1}{\mathbf{s}^* \mathbf{R}^{-1} \mathbf{s}} \end{aligned} \quad (5.23)$$

가

.

4

가 $M-1$

.

$$\hat{x}_m = - \sum_{m \neq m_0} \overline{w}_m x_m \quad (5.24)$$

$$, \quad \hat{x}_m \quad (5.24)$$

[37].

, 가

가 .

e_m

\mathbf{w}

.

$$e_m = x_m - \hat{x}_m = x_{m_0} + \sum_{m \neq m_0} \overline{w}_m x_m \quad (5.25)$$

$$(5.25) \quad .$$

$$\begin{aligned} e_m &= \overline{w}_0 x_0 + \overline{w}_1 x_1 + \overline{w}_2 x_2 + \dots + \overline{w}_{M-1} x_{M-1} \\ &= \mathbf{w}^* \mathbf{x} \end{aligned} \quad (5.26)$$

\mathbf{w} .

$$\mathbf{w} = [w_0, w_1, \dots, w_{m_0-1}, w_{m_0}, w_{m_0+1}, \dots, w_{M-1}]^T$$

$$w_{m_0} = 1 \qquad E \left[|e_m|^2 \right]$$

$$\mathbf{w} \qquad \qquad \qquad \mathbf{w}^* \boldsymbol{\mu}_{\mathbf{m}_0} = 1$$

$$\boldsymbol{\mu}_{\mathbf{m}_0} \qquad m_0 \qquad \qquad \qquad \text{가 } 1$$

$$0 \qquad \qquad \qquad .$$

MLM

Lagrange multiplier .

$$F = \mathbf{w}^* \mathbf{R} \mathbf{w} + \alpha (\mathbf{w}^* \boldsymbol{\mu}_{\mathbf{m}_0} - 1) \tag{5.27}$$

$$\mathbf{w} \qquad \qquad \qquad .$$

$$\mathbf{w} = \frac{\mathbf{R}^{-1} \boldsymbol{\mu}_{\mathbf{m}_0}}{\boldsymbol{\mu}_{\mathbf{m}_0}^* \mathbf{R}^{-1} \boldsymbol{\mu}_{\mathbf{m}_0}} \tag{5.28}$$

$$,$$

all-pole model

$$.$$

$$P(\mathbf{u}) = |H(e^{j\omega})|^2 = \frac{1}{\left| 1 + \sum_{m \neq m_0}^n w_m e^{-jm\omega} \right|^2} \tag{5.29}$$

$$(5.29) \qquad \qquad \qquad .$$

$$P(\mathbf{u}) = \frac{1}{\left| \mathbf{w}^* \mathbf{s} \right|^2} \tag{5.30}$$

$$(5.28) \qquad \mathbf{w} \qquad \qquad \qquad (5.30)$$

$$.$$

$$P_{LPM}(\mathbf{u}) = \frac{\left(\boldsymbol{\mu}_{m_0}^* \mathbf{R}^{-1} \boldsymbol{\mu}_{m_0}\right)^2}{\left|\boldsymbol{\mu}_{m_0}^* \mathbf{R}^{-1} \mathbf{s}\right|^2} \tag{5.31}$$

MLM [44].

MLM

(weight) MLM
가
ripple

5 MUSIC (Multiple Signal Classification)

1981 Schmidt[39] MUSIC
eigen- analysis가

N ($\mathbf{R}_\eta = \mathbf{I}$)
가 $M \times M$ \mathbf{R} N
 N
span $M - N$
span \mathbf{R}
 λ_m \mathbf{v}_m

$$\mathbf{R} = \sum_{m=1}^M \lambda_m \mathbf{v}_m \mathbf{v}_m^* \quad (5.32)$$

$$\mathbf{R}^{-1} = \sum_{m=1}^M \frac{1}{\lambda_m} \mathbf{v}_m \mathbf{v}_m^* \quad (5.33)$$

span $M - N$
 \mathbf{R}_{EV} \mathbf{R}_{EV} [40][45].

$$\mathbf{R}_{\text{EV}}^{-1} = \sum_{m=1}^{M-N} \frac{1}{\lambda_m} \mathbf{v}_m \mathbf{v}_m^* \quad (5.34)$$

가 EVM (Eigenvector Method)
 가

$$\mathbf{w} = \frac{\mathbf{R}_{\text{EV}}^{-1} \mathbf{s}}{\mathbf{s}^* \mathbf{R}_{\text{EV}}^{-1} \mathbf{s}} \quad (5.35)$$

. (5.34) (5.23)
 .

$$\begin{aligned} P(\mathbf{u}) &= \frac{1}{\mathbf{s}^* \mathbf{R}^{-1} \mathbf{s}} \\ &= \left[\mathbf{s}^* \left(\sum_{m=1}^{M-N} \frac{1}{\lambda_m} \mathbf{v}_m \mathbf{v}_m^* \right) \mathbf{s} \right]^{-1} \\ &= \left(\sum_{m=1}^{M-N} \frac{1}{\lambda_m} |\mathbf{s}^* \mathbf{v}_m|^2 \right)^{-1} \end{aligned} \quad (5.36)$$

\mathbf{s} 가
 $\mathbf{s}^* \mathbf{v}_m = 0$
 가 0 가 .

Multiple Signal Classification (MUSIC)

(\mathbf{R}_{EV})

$$\mathbf{R}_M^{-1} = \sum_{m=1}^{M-N} \mathbf{v}_m \mathbf{v}_m^* \quad (5.37)$$

$$\mathbf{R} \mathbf{v}_m = \lambda_m \mathbf{v}_m, \quad \mathbf{v}_m^T \mathbf{S} = 0$$

, λ_m

$$\mathbf{R} \mathbf{v}_m = \lambda_m \mathbf{v}_m \quad (5.38)$$

$$(\sigma_\eta^2 \mathbf{I} + \sigma_s^2 \mathbf{S} \mathbf{S}^*) \mathbf{S} = (\sigma_\eta^2 + M \sigma_s^2) \mathbf{S}$$

$$\therefore \lambda_m = \sigma_\eta^2 + M \sigma_s^2 \quad (5.39)$$

$$M - N \quad \sigma_n^2$$

S

MUSIC

.

$$P_M(\mathbf{u}) = \left(\sum_{m=1}^{M-N} \frac{1}{\sigma_\eta^2} |\mathbf{s}^* \mathbf{v}_m|^2 \right)^{-1} \quad (5.40)$$

가

.

6 AOA

2

,

.

$$y = \tan \theta_i (x - x_i) + y_i \quad (5.41)$$

$x, y :$

$x_i, y_i : i$

$\theta_i :$ i 가

$$\text{AOA} \quad , \quad (5.41)$$

.

$$\mathbf{H}\mathbf{X} = \mathbf{Y} \quad (5.42)$$

,

$$\mathbf{H} = \begin{bmatrix} \tan \theta_1 & -1 \\ \tan \theta_2 & -1 \end{bmatrix}, \quad \mathbf{X} = [x \ y]^T, \quad \mathbf{Y} = \begin{bmatrix} \tan \theta_1 x_1 - y_1 \\ \tan \theta_2 x_2 - y_2 \end{bmatrix}$$

n

.

$$\mathbf{X} = (\mathbf{H}^T \mathbf{H})^{-1} \mathbf{H}^T \mathbf{Y} \quad (5.43)$$

7

1.

4가

.

가

.

가 0.25

가

1 ,

0° 가 . ,

0 dB .

, , 가

• :

$$\frac{1}{L} \sum_i (\alpha - \hat{\alpha}_i) \quad (5.44)$$

• :

$$\sqrt{\frac{1}{L} \sum_{i=1}^L (\hat{\alpha}_i - \alpha_m)^2} \quad (5.45)$$

• :

$$\frac{1}{L} \sum_{i=1}^L (\alpha - \hat{\alpha}_i)^2 \quad (5.46)$$

L , , $\hat{\alpha}_i$
, m L $\hat{\alpha}_i$

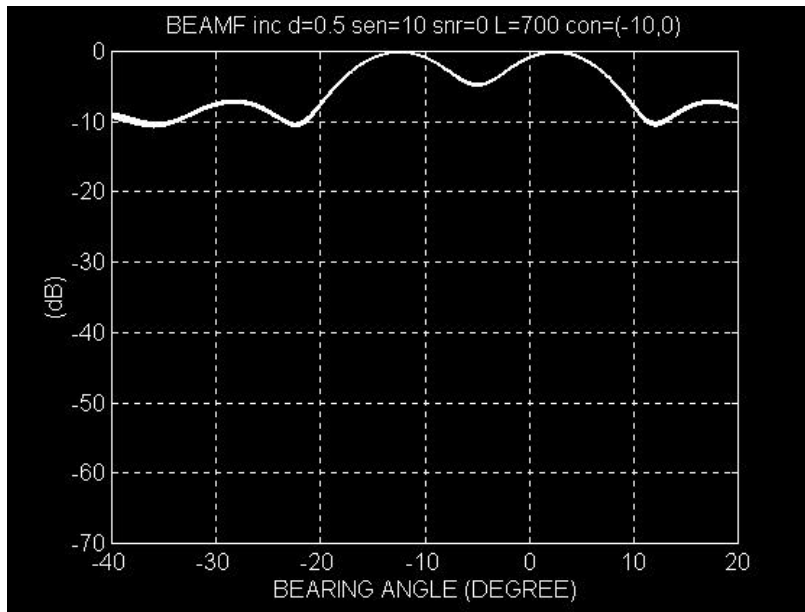
·
- 10 ° 0 ° 가
10 가

· $d = 0.5$. 가
0.25

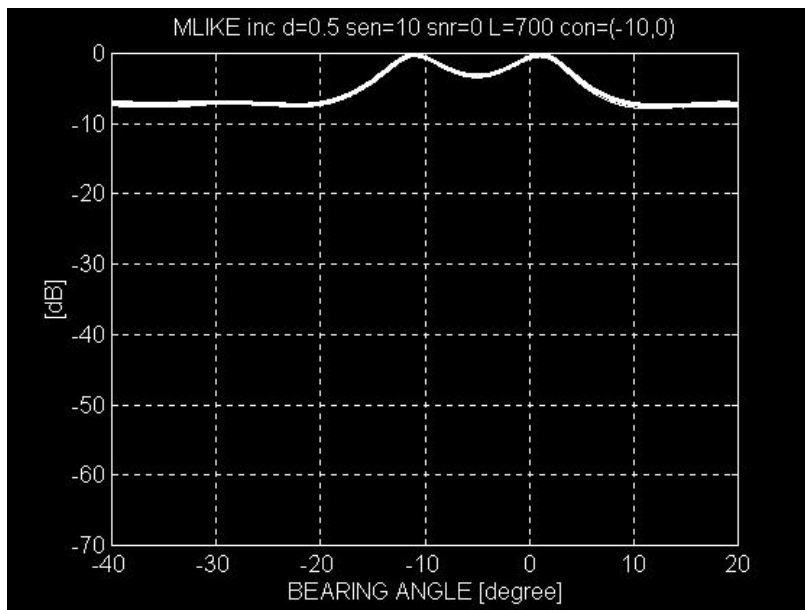
가 700 .

(5.2), (5.3), (5.4), (5.5) , MLM,
LPM, MUSIC SNR 0 dB 10

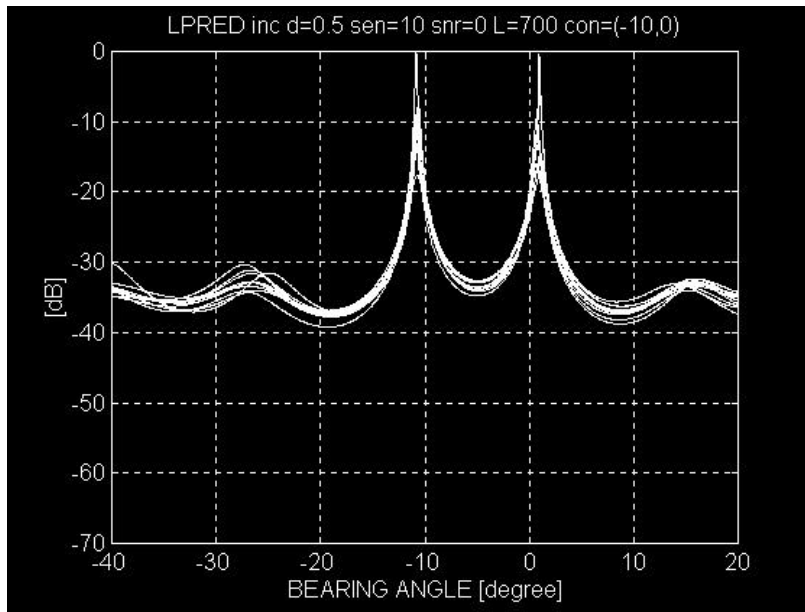
가 . MLM LPM 0 dB 2 °
MUSIC
.
SNR 700
, 300 . (5.6) (5.8)
.
가 MUSIC 가
.



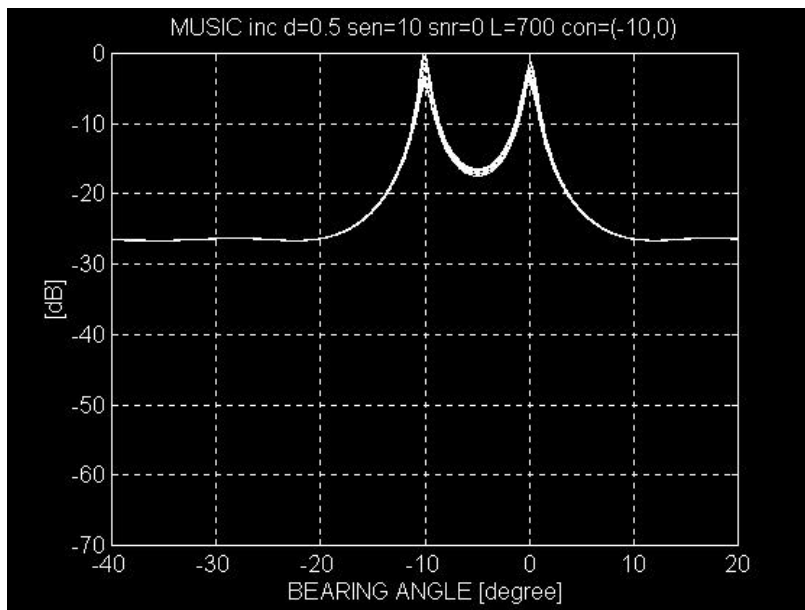
(5.2) (L=700, SNR=0, $\theta = -10^\circ, 0^\circ$)



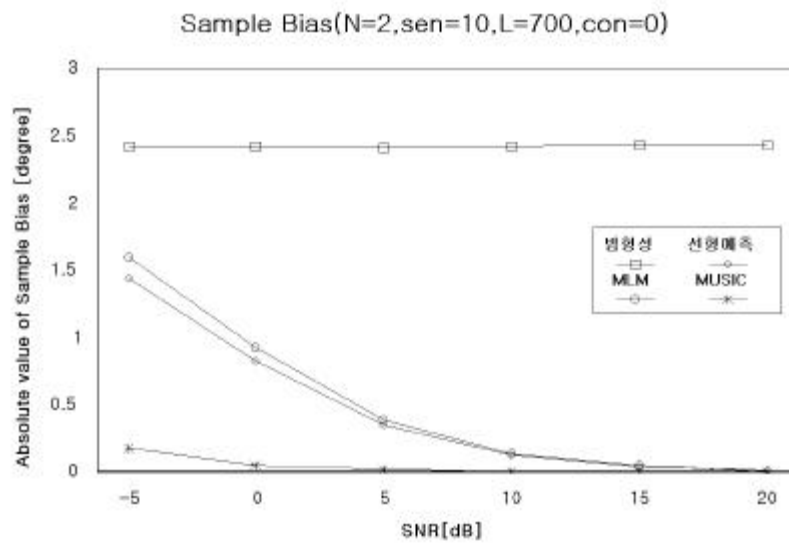
(5.3) MLM (L=700, SNR=0, $\theta = -10^\circ, 0^\circ$)



(5.4) (L=700, SNR=0, $\theta = -10^\circ, 0^\circ$)

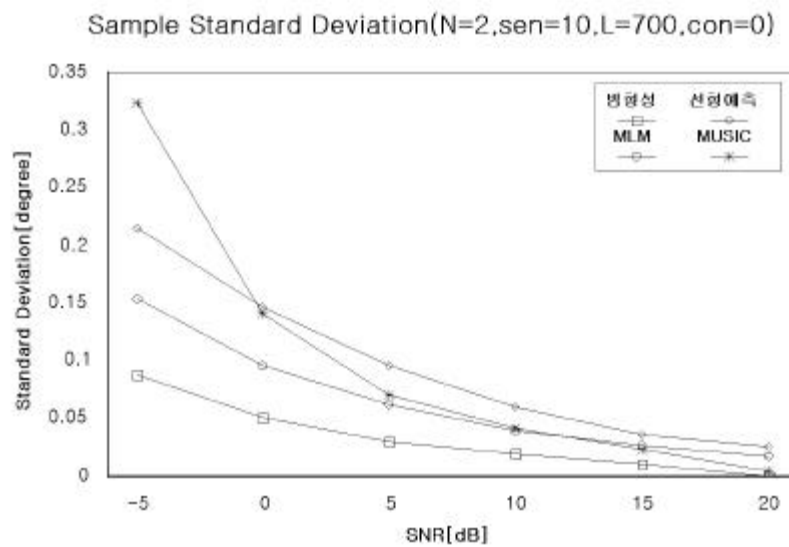


(5.5) MUSIC (L=700, SNR=0, $\theta = -10^\circ, 0^\circ$)



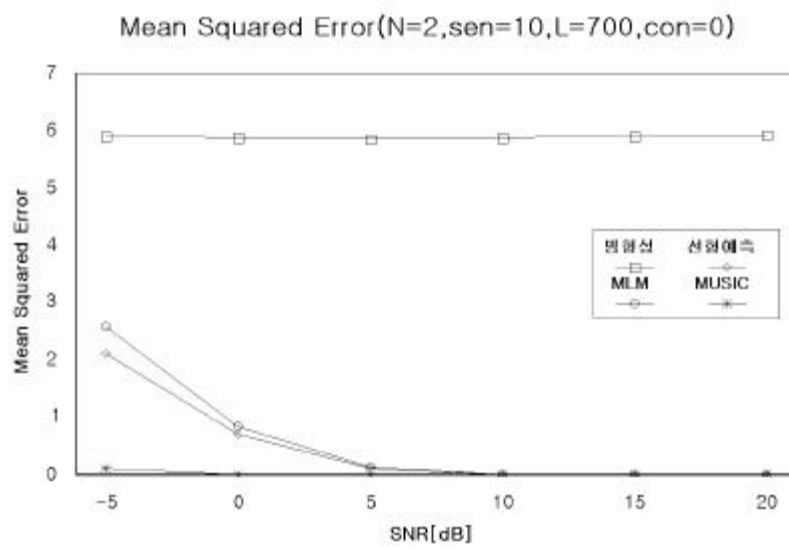
(5.6) 2

(M=10, L=700, $\theta = 0^\circ$)



(5.7) 2

(M=10, L=700, $\theta = 0^\circ$)



(5.8) 2

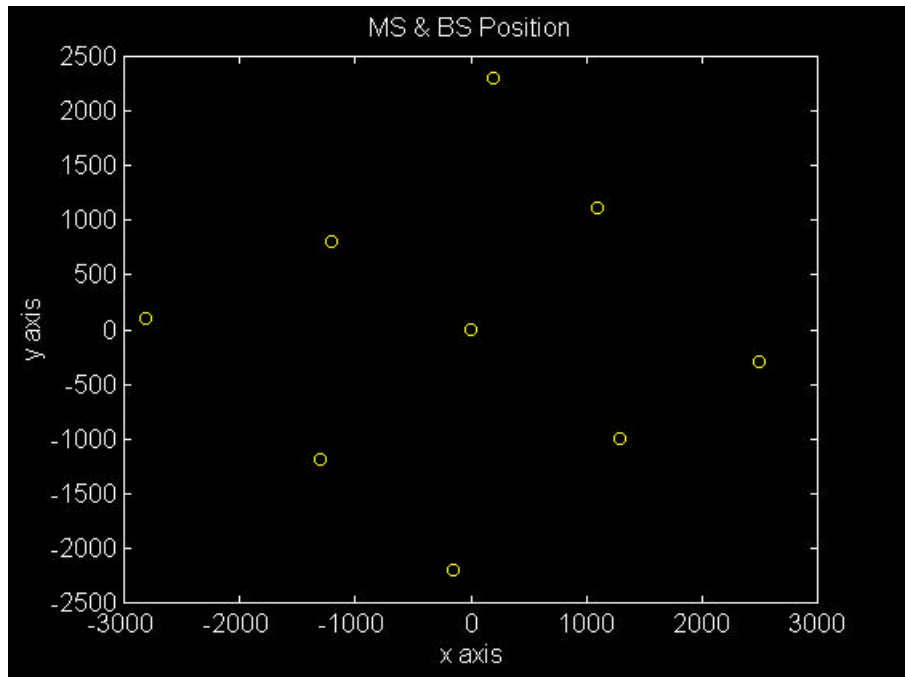
(M=10, L=700, =0 °)

2. AOA

6
가
0.3 °
가
(5.1), (5.9)
(- 800,100), (800,100) 가 .

(5.1) (: m)

	(x,y)		(x,y)
BS1	(0, 0)	BS6	(2500, - 300)
BS2	(1100, 1100)	BS7	(200, 2300)
BS3	(1300, - 1000)	BS8	(- 2800, 100)
BS4	(- 1200, 800)	BS9	(- 150, - 2200)
BS5	(- 1300, - 1200)		



(5.9)

가 .

$$MSE = E[(x - x^0)^2 + (y - y^0)^2] \tag{5.47}$$

1000 . 가 3 BS1, BS2, BS3 가

(5.2) 가 (- 800,100)

(800,100) . 가 5

6 가 . (

5.10) 가 (- 800,100) 3

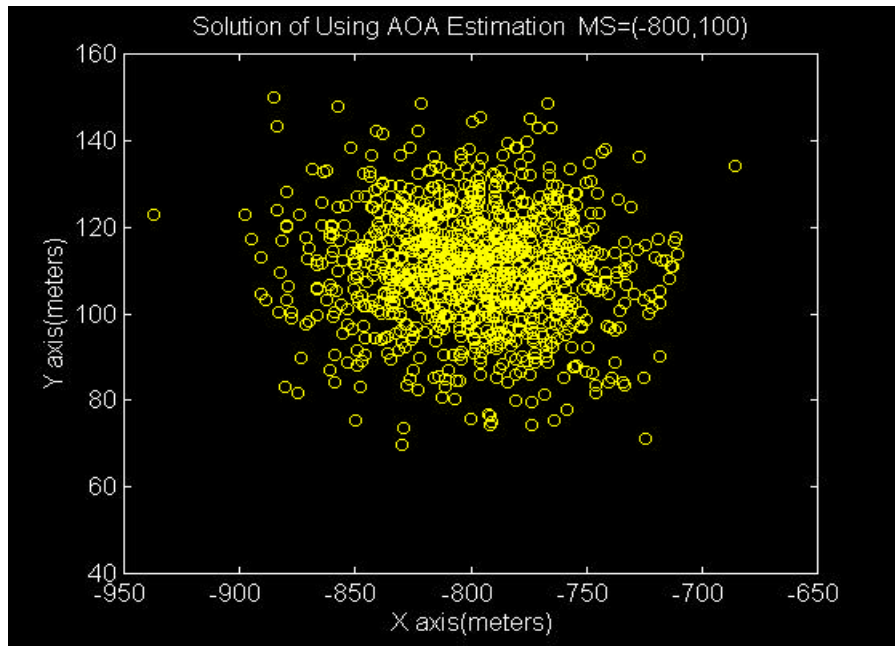
$$(5.11) 5$$

. 5 가 3

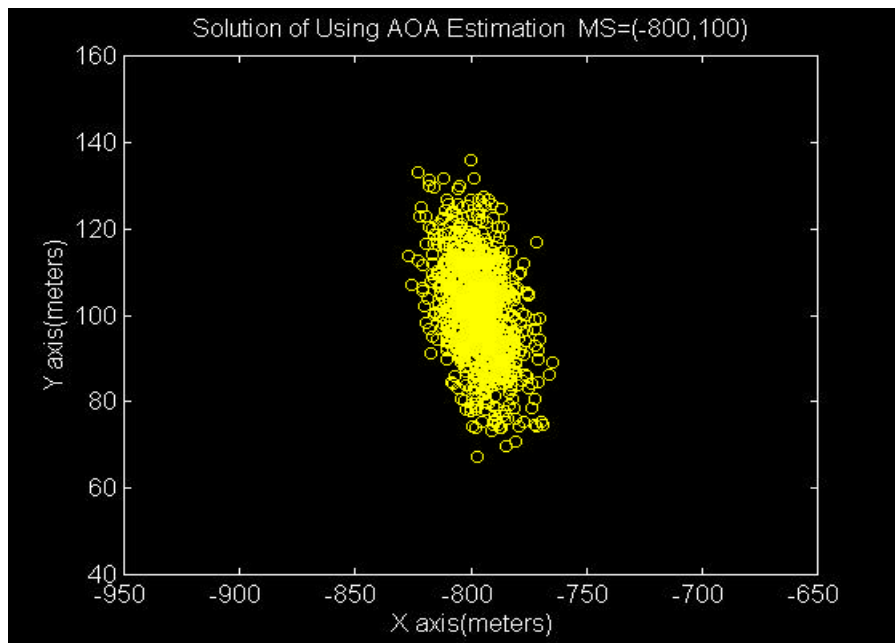
가 (800,100) 3 , 5 . (5.12) (5.13) .
가 5 가 가 .
가
가 AOA 가
.

(5.2)

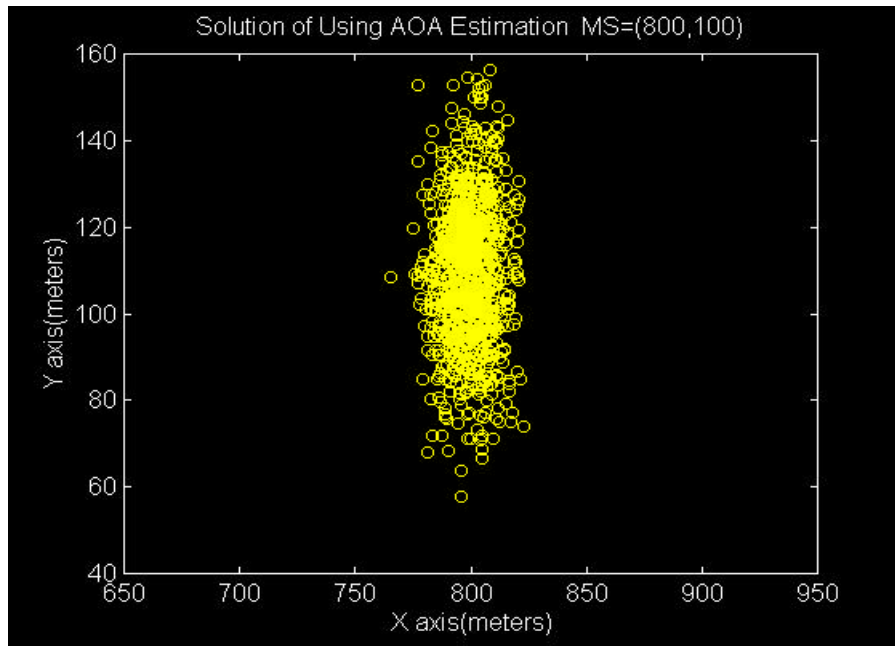
	3	4	5	6	7	8	9
(- 800,100)	1542.2	489.6901	241.1486	257.8430	279.3471	232.6128	467.6441
(800,100)	453.7650	286.0629	236.9448	202.3054	409.4794	396.9726	467.4876



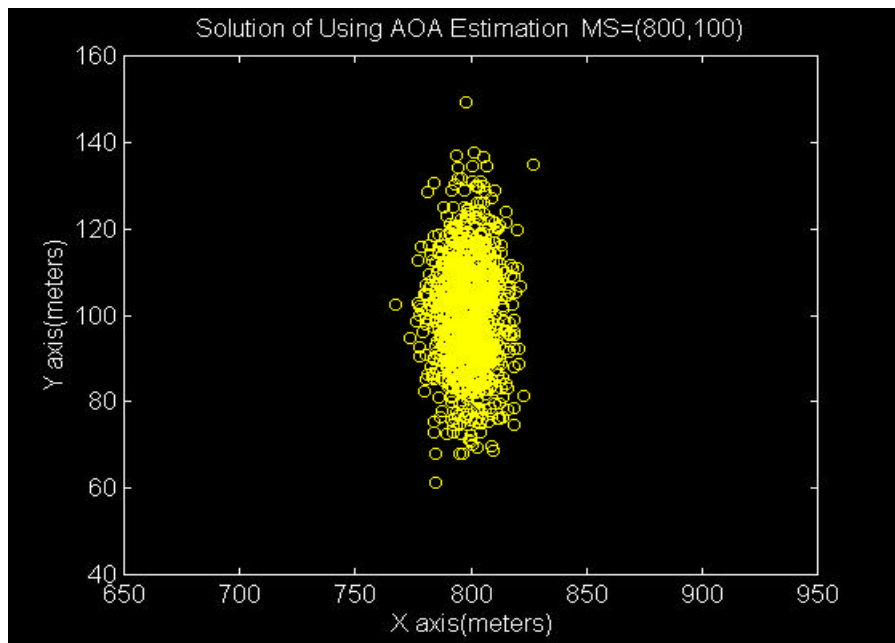
(5.10) 가 3 (MS=- 800,100)



(5.11) 가 5 (MS=- 800,100)



(5.12) 가 3 (MS=800,100)



(5.13) 가 5 (MS=800,100)

6 TDOA (Chan's Method)

,
 .
 (TDOA) .
 Carter[14], Hahn[13][46], Abel
 and Smith[16]
 TDOA 가
 가 .
 가 TDOA
 . Fang[47] TDOA 가 ()
 .
 .
 Friedlander[48], Schau and Robinson[49], , Smith- Abel[50][51]
 . closed-form 가
 . Abel divide and conquer(DAC)
 Fisher 가 .
 Taylor
 - series .
 가 .
 가 .
 가 .

Chan[53] closed- form ,

.

1

2

3

. (6.1)

M

가

.

i

.

$$u_i(k) = s(k - d_i) + \eta_i(k), \quad i = 1, 2, \dots, M \quad (6.1)$$

, $s(k)$

, d_i i

, $\eta_i(k)$ 가 .

, 0 가 .

i j

TDOA . Generalized cross

- correlation 가

TDOA

TDOA .

$$d_{i,1} = d_i - d_1 \quad \text{for } i = 2, 3, \dots, M \quad (6.2)$$

i j TDOA .

$$d_{i,j} = d_{i,1} - d_{j,1} \quad \text{for } i, j = 2, 3, \dots, M \quad (6.3)$$

$$\mathbf{d} = [d_{2,1}, d_{3,1}, \dots, d_{M,1}]^T \quad \text{TDOA} \quad . \quad d_{i,j}^0$$

TDOA $d_{i,j}$.

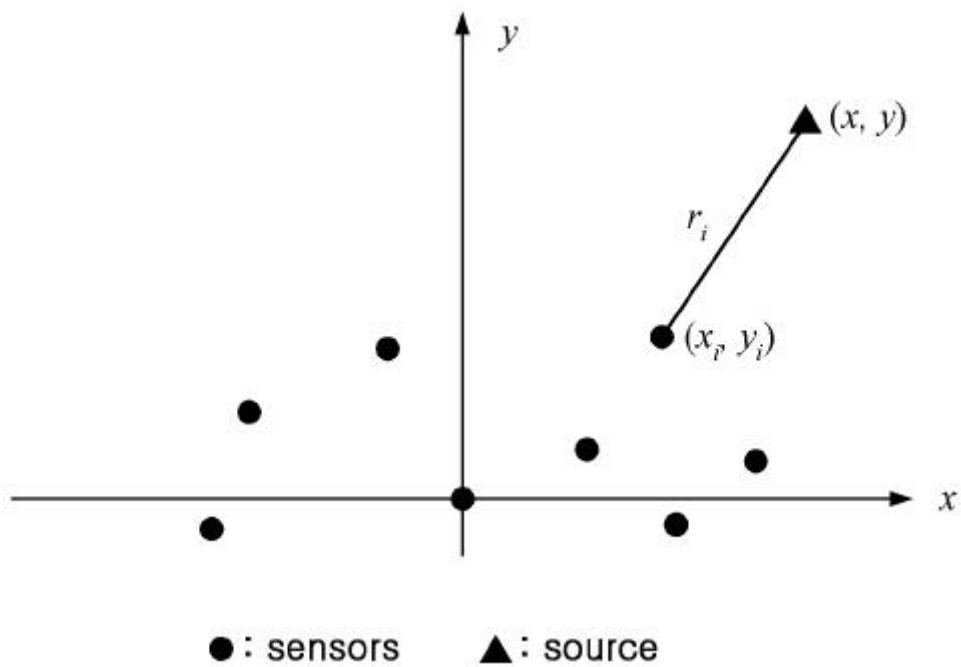
$$d_{i,j} = d_{i,j}^0 + n_{i,j} \quad \text{for } i, j = 2, 3, \dots, M \quad (6.4)$$

$$n_{i,j} \quad (\quad)$$

$$n_{i,j} = n_{i,1} - n_{j,1} \quad . \quad \mathbf{n} = [n_{2,1}, n_{3,1}, \dots, n_{M,1}]^T \quad .$$

$$\text{TDOA} \quad \text{가} \quad \text{가} \quad \mathbf{n} \quad 0$$

$$\text{TDOA} \quad \mathbf{d} \quad \mathbf{Q} \quad .$$



$$(\quad 6.1)$$

$$\begin{aligned}
& \sum_{i=1}^M \left[\frac{1}{2} (x_i - x)^2 + \frac{1}{2} (y_i - y)^2 \right] \\
& = \frac{1}{2} \sum_{i=1}^M (x_i^2 + y_i^2) - \sum_{i=1}^M (x_i x + y_i y) + \frac{M}{2} (x^2 + y^2) \\
& = \frac{1}{2} K_i - \sum_{i=1}^M (x_i x + y_i y) + \frac{M}{2} (x^2 + y^2), \quad i = 1, 2, \dots, M
\end{aligned}
\tag{6.5}$$

$$K_i = x_i^2 + y_i^2$$

$$r_{i,1} = cd_{i,1} = r_i - r_1 \tag{6.6}$$

$$c = \frac{1}{M} \sum_{i=1}^M (x_i - x)^2 + \frac{1}{M} \sum_{i=1}^M (y_i - y)^2$$

Taylor-series (6.6)

$$\begin{aligned}
& \frac{1}{2} \sum_{i=1}^M (x_i - x)^2 + \frac{1}{2} \sum_{i=1}^M (y_i - y)^2 \\
& = \frac{1}{2} \sum_{i=1}^M (x_i^2 + y_i^2) - \sum_{i=1}^M (x_i x + y_i y) + \frac{M}{2} (x^2 + y^2)
\end{aligned}$$

$$\begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = (\mathbf{G}_t^T \mathbf{Q}^{-1} \mathbf{G}_t)^{-1} \mathbf{G}_t^T \mathbf{Q}^{-1} \mathbf{h}_t \tag{6.7}$$

$$\mathbf{h}_t = \begin{bmatrix} r_{2,1} - (r_2 - r_1) \\ r_{3,1} - (r_3 - r_1) \\ \vdots \\ r_{M,1} - (r_M - r_1) \end{bmatrix}$$

$$\mathbf{G}_t = \begin{bmatrix} (x_1 - x)/r_1 - (x_2 - x)/r_2 & (y_1 - y)/r_1 - (y_2 - y)/r_2 \\ (x_1 - x)/r_1 - (x_3 - x)/r_3 & (y_1 - y)/r_1 - (y_3 - y)/r_3 \\ \vdots & \vdots \\ (x_1 - x)/r_1 - (x_M - x)/r_M & (y_1 - y)/r_1 - (y_M - y)/r_M \end{bmatrix}$$

$$x = x_0, \quad y = y_0 \quad x_0 + \Delta x, \\ y_0 + \Delta y \text{가} \quad \Delta x, \Delta y \text{가}$$

1. 3 (M=3)

$$(6.6) \quad r_i^2 = (r_{i,1} + r_1)^2 \quad (6.5)$$

$$r_{i,1}^2 + 2r_{i,1}r_1 + r_1^2 = K_{i-} - 2x_{i-} - 2y_{i-} + x^2 + y^2 \quad (6.8)$$

$$(6.8) \quad i = 1 \quad (6.5)$$

$$r_{i,1}^2 + 2r_{i,1}r_1 = -2x_{i,1}x - 2y_{i,1}y + K_{i-} - K_1 \quad (6.9)$$

$$\begin{bmatrix} x \\ y \end{bmatrix} = - \begin{bmatrix} x_{2,1} & y_{2,1} \\ x_{3,1} & y_{3,1} \end{bmatrix}^{-1} \times \left\{ \begin{bmatrix} r_{2,1} \\ r_{3,1} \end{bmatrix} r_1 + \frac{1}{2} \begin{bmatrix} r_{2,1}^2 & K_{2+} & K_1 \\ r_{3,1}^2 & K_{3+} & K_1 \end{bmatrix} \right\} \quad (6.10)$$

$$i = 1 \quad (6.5) \quad r_1 \quad 2$$

2. 4

가 .

, (6.9) .

가 .

$$\mathbf{z}_a = [\mathbf{z}_p^T, r_1]^T \quad \text{where} \quad \mathbf{z}_p = [x, y]^T \quad (6.11)$$

\mathbf{z}_a . TDOA (6.9)

가 .

$$\phi = \mathbf{h} - \mathbf{G}_a \mathbf{z}_a^0 \quad (6.12)$$

$$\mathbf{h} = \frac{1}{2} \begin{bmatrix} r_{2,1}^2 - K_2 + K_1 \\ r_{3,1}^2 - K_3 + K_1 \\ \vdots \\ r_{M,1}^2 - K_M + K_1 \end{bmatrix}$$

$$\mathbf{G}_a = \begin{bmatrix} x_{2,1} & y_{2,1} & r_{2,1} \\ x_{3,1} & y_{3,1} & r_{3,1} \\ \vdots & \vdots & \vdots \\ x_{M,1} & y_{M,1} & r_{M,1} \end{bmatrix}$$

. (6.4) $r_{i,1} = r_{i,1}^0 + cn_{i,1}$

(6.6) $r_i^0 = r_{i,1}^0 + r_1^0 \quad \phi$

.

$$\phi = c \mathbf{B} \mathbf{n} + 0.5 c^2 \mathbf{n} \odot \mathbf{n} \quad (6.13)$$

$$\text{where } \mathbf{B} = \text{diag}\{r_2^0, r_3^0, \cdots, r_M^0\}$$

$$\odot \quad \text{Schur} \quad (\text{element-by-element}) \quad .$$

가 generalized cross-correlantion

TDOA 가 .

$$\mathbf{n} \quad \phi$$

$$cn_{i,1} \ll r_i \quad (6.13)$$

$$\text{가} \quad \text{가} \quad .$$

$$\boldsymbol{\Psi} = E[\boldsymbol{\phi} \boldsymbol{\phi}^T] = c^2 \mathbf{B} \mathbf{Q} \mathbf{B} \quad (6.14)$$

$$\mathbf{z}_a \quad (6.5) \quad x \quad y$$

. x, y, r_1

$$\text{가} \quad .$$

$$(6.5)$$

$$\text{ML(Maximum Likelihood)} \quad . \quad \mathbf{z}_a$$

$$\text{가} \quad \mathbf{z}_a \quad \text{ML} \quad .$$

$$\begin{aligned} \mathbf{z}_a &= \arg \min \{ (\mathbf{h} - \mathbf{G}_a \mathbf{z}_a)^T \boldsymbol{\Psi}^{-1} (\mathbf{h} - \mathbf{G}_a \mathbf{z}_a) \} \\ &= (\mathbf{G}_a^T \boldsymbol{\Psi}^{-1} \mathbf{G}_a)^{-1} \mathbf{G}_a^T \boldsymbol{\Psi}^{-1} \mathbf{h} \end{aligned} \quad (6.15)$$

$$(6.15) \quad (6.12) \quad .$$

$$\mathbf{B} \quad \boldsymbol{\Psi}$$

$$\text{가} \quad r_i^0 \quad r^0$$

$$\mathbf{B} \approx r^0 \mathbf{I} \quad (6.16)$$

$$r^0, \quad \mathbf{I} \quad M-1 \quad \psi \quad (6.15)$$

$$\mathbf{z}_a = (\mathbf{G}_a^T \mathbf{Q}^{-1} \mathbf{G}_a)^{-1} \mathbf{G}_a^T \mathbf{Q}^{-1} \mathbf{h} \quad (6.17)$$

$$\text{가} \quad \mathbf{B} \quad (6.17) \quad (6.15)$$

$$(6.15)$$

$$\mathbf{z}_a \quad (6.15) \quad \mathbf{z}_a \quad \mathbf{z}_a \mathbf{z}_a^T$$

$$r_{i,1} \quad \mathbf{G}_a$$

$$\text{(perturbation approach)}$$

$$r_{i,1} = r_{i,1}^0 + cn_{i,1}, \quad \mathbf{G}_a$$

$$\mathbf{h} \quad \mathbf{G}_a = \mathbf{G}_a^0 + \Delta \mathbf{G}_a \quad \mathbf{h} = \mathbf{h}^0 + \Delta \mathbf{h} \quad (6.12)$$

$$\phi = \Delta \mathbf{h} - \Delta \mathbf{G}_a \mathbf{z}_a^0 \quad (6.18)$$

$$\mathbf{z}_a = \mathbf{z}_a^0 + \Delta \mathbf{z}_a \quad (6.15)$$

$$\begin{aligned} & (\mathbf{G}_a^{0T} + \Delta \mathbf{G}_a^T) \boldsymbol{\Psi}^{-1} (\mathbf{G}_a^0 + \Delta \mathbf{G}_a) (\mathbf{z}_a^0 + \Delta \mathbf{z}_a) \\ &= (\mathbf{G}_a^{0T} + \Delta \mathbf{G}_a^T) \boldsymbol{\Psi}^{-1} (\mathbf{h} + \Delta \mathbf{h}) \end{aligned} \quad (6.19)$$

$$(6.13) \quad (6.18) \quad \mathbf{z}_a,$$

$$\Delta \mathbf{z}_a \quad .$$

$$\Delta \mathbf{z}_a = c (\mathbf{G}_a^{0T} \boldsymbol{\Psi}^{-1} \mathbf{G}_a^0)^{-1} \mathbf{G}_a^{0T} \boldsymbol{\Psi}^{-1} \mathbf{B} \mathbf{n} \quad (6.20)$$

$$\text{cov}(\mathbf{z}_a) = \mathbb{E}[\Delta \mathbf{z}_a \Delta \mathbf{z}_a^T] = (\mathbf{G}_a^{0T} \boldsymbol{\Psi}^{-1} \mathbf{G}_a^0)^{-1} \quad (6.21)$$

$$(6.13) \quad (6.14)$$

$$\text{cov}(\mathbf{z}_a) \quad .$$

$$\mathbf{z}_a \quad x, y \quad r_1 \quad \text{가} \quad . \quad i=1$$

$$(6.5) \quad .$$

$$\text{가}$$

$$\text{가} \quad (\quad \text{TDOA} \quad .) \quad \mathbf{z}_a$$

$$(6.21) \quad . \quad ,$$

$$\mathbf{z}_a \quad .$$

$$z_{a,1} = x^0 + e_1 \quad , \quad z_{a,2} = y^0 + e_2 \quad , \quad z_{a,3} = r_1^0 + e_3 \quad (6.22)$$

$$, \quad e_1, e_2 \quad e_3 \quad \mathbf{z}_a \quad . \quad \mathbf{z}_a$$

$$x_1, y_1$$

$$.$$

$$\phi' = \mathbf{h}' - \mathbf{G}_a' \mathbf{z}_a'^0 \quad (6.23)$$

$$\text{cov}(\mathbf{z}_a) \approx c^2 r^{02} (\mathbf{G}_a^{0T} \mathbf{Q}^{-1} \mathbf{G}_a^0)^{-1} \quad (6.27)$$

$$(6.26) \quad .$$

$$\mathbf{z}_a \approx (\mathbf{G}_a'^T \mathbf{B}'^{-1} \mathbf{G}_a^T \mathbf{Q}^{-1} \mathbf{G}_a \mathbf{B}'^{-1} \mathbf{G}_a')^{-1} (\mathbf{G}_a'^T \mathbf{B}'^{-1} \mathbf{G}_a^T \mathbf{Q}^{-1} \mathbf{G}_a \mathbf{B}'^{-1}) \mathbf{h}' \quad (6.28)$$

$$\mathbf{G}_a' \quad . \quad \mathbf{z}_a' \quad .$$

$$\text{cov}(\mathbf{z}_a) = (\mathbf{G}_a'^T \boldsymbol{\Psi}^{-1} \mathbf{G}_a')^{-1} \quad (6.29)$$

$$.$$

$$\mathbf{z}_p = \pm \sqrt{\mathbf{z}_a'} + \begin{bmatrix} x_1 \\ y_1 \end{bmatrix} \quad (6.30)$$

$$. \quad \mathbf{z}_a'$$

$$\text{가 } 0 \quad \text{가} \quad (6.30) \quad \text{가}$$

$$0 \quad .$$

$$x = x^0 + e_x, \quad y = y^0 + e_y$$

$$. \quad (6.23) \quad .$$

$$z_{a,1}' - (x^0 - x_1)^2 = 2(x^0 - x_1)e_x + e_x^2$$

$$z_{a,2}' - (y^0 - y_1)^2 = 2(y^0 - y_1)e_y + e_y^2 \quad (6.31)$$

$$e_x \quad e_y \quad x^0 \quad y^0 \quad e_x^2 \quad e_y^2$$

$$\mathbf{z}_p \quad .$$

$$\begin{aligned}
\Phi &= \text{cov}(\mathbf{z}_p) = \frac{1}{4} \mathbf{B}''^{-1} \text{cov}(\mathbf{z}_a') \mathbf{B}''^{-1} \\
&= c^2 (\mathbf{B}'' \mathbf{G}_a'^T \mathbf{B}''^{-1} \mathbf{G}_a^{0T} \mathbf{B}^{-1} \mathbf{Q}^{-1} \mathbf{B}^{-1} \mathbf{G}_a^0 \mathbf{B}''^{-1} \mathbf{G}_a' \mathbf{B}'')^{-1}
\end{aligned} \tag{6.32}$$

$$\text{where } \mathbf{B}'' = \begin{bmatrix} (x^0 - x_1) & 0 \\ 0 & (y^0 - y_1) \end{bmatrix}$$

(6.15), (6.26) (6.30)

$$. \quad (6.15) \quad (6.26)$$

가

$$(6.17), \quad (6.28), \quad (6.30) \quad . \quad \text{가}$$

$$(6.17) \quad \mathbf{B} \quad (6.15),$$

$$(6.26), \quad (6.30) \quad .$$

2 CRLB

Cramér-Rao [52] 가

CRLB

.

CRLB(Cramér-Rao Lower Bound)

.

$$\Phi^0 = c^2 (\mathbf{G}_t^{0T} \mathbf{Q}^{-1} \mathbf{G}_t^0)^{-1} \tag{6.33}$$

$$\mathbf{G}_t^0(x, y, r_i) = (x^0, y^0, r_i^0) \tag{7}$$

$$(6.32) \quad . \quad (6.12),$$

$$(6.13), \quad (6.25) \quad (6.26) \quad .$$

$$\begin{aligned}
[\mathbf{B}^{-1}\mathbf{G}_a^0\mathbf{B}'^{-1}]_{i-1,1} &= \frac{-x_{i,1}}{(x_1^0-x_1)r_i^0} \\
[\mathbf{B}^{-1}\mathbf{G}_a^0\mathbf{B}'^{-1}]_{i-1,2} &= \frac{-y_{i,1}}{(y_1^0-y_1)r_i^0} \\
[\mathbf{B}^{-1}\mathbf{G}_a^0\mathbf{B}'^{-1}]_{i-1,3} &= \frac{-r_{i,1}^0}{r_1^0r_i^0}
\end{aligned} \tag{6.34}$$

$$[\mathbf{R}]_{i,j} = \mathbf{R}(i,j), \tag{6.23}$$

$$(6.32) \quad \mathbf{G}_a' = \mathbf{B}''$$

.

$$\begin{aligned}
[\mathbf{B}^{-1}\mathbf{G}_a^0\mathbf{B}'^{-1}\mathbf{G}_a'\mathbf{B}']_{i-1,1} &= -(x_1^0-x_1)\left\{\frac{x_{i,1}}{(x_1^0-x_1)r_i^0}+\frac{r_{i,1}^0}{r_1^0r_i^0}\right\} \\
&= [\mathbf{G}_t^0]_{i-1,1} \\
[\mathbf{B}^{-1}\mathbf{G}_a^0\mathbf{B}'^{-1}\mathbf{G}_a'\mathbf{B}']_{i-1,2} &= [\mathbf{G}_t^0]_{i-1,2}
\end{aligned} \tag{6.35}$$

$$\mathbf{G}_t^0.$$

$$\mathbf{B}^{-1}\mathbf{G}_a^0\mathbf{B}'^{-1}\mathbf{G}_a'\mathbf{B}'' = \mathbf{G}_t^0 \tag{6.36}$$

$$(6.36) \quad (6.33) \quad \text{CRLB}.$$

3

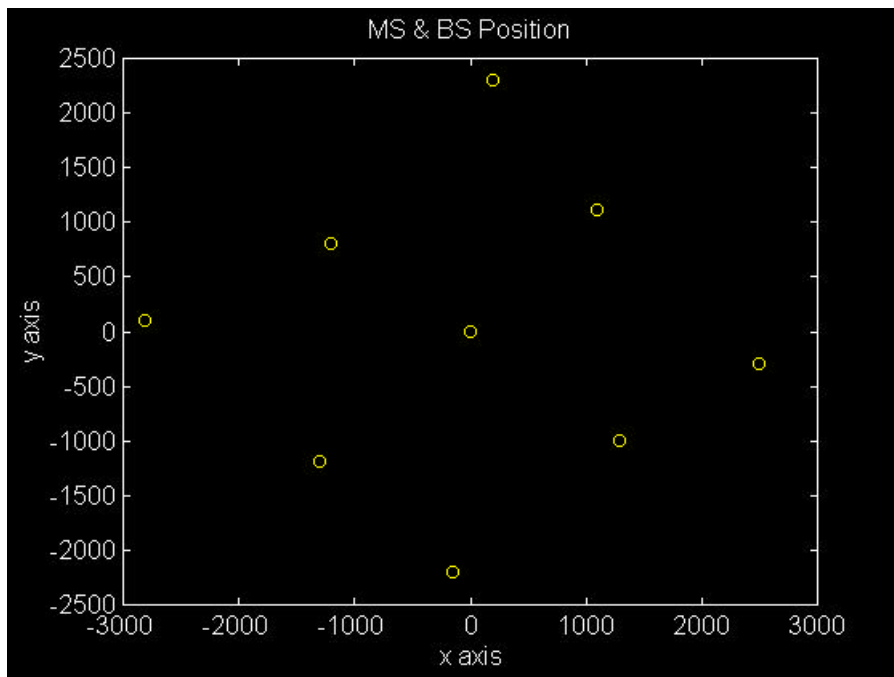
TDOA

. (

6.1),(6.2) .

(6.1) (: m)

	(x,y)		(x,y)
BS1	(0, 0)	BS6	(2500, - 300)
BS2	(1100, 1100)	BS7	(200, 2300)
BS3	(1300, - 1000)	BS8	(- 2800, 100)
BS4	(- 1200, 800)	BS9	(- 150, - 2200)
BS5	(- 1300, - 1200)		



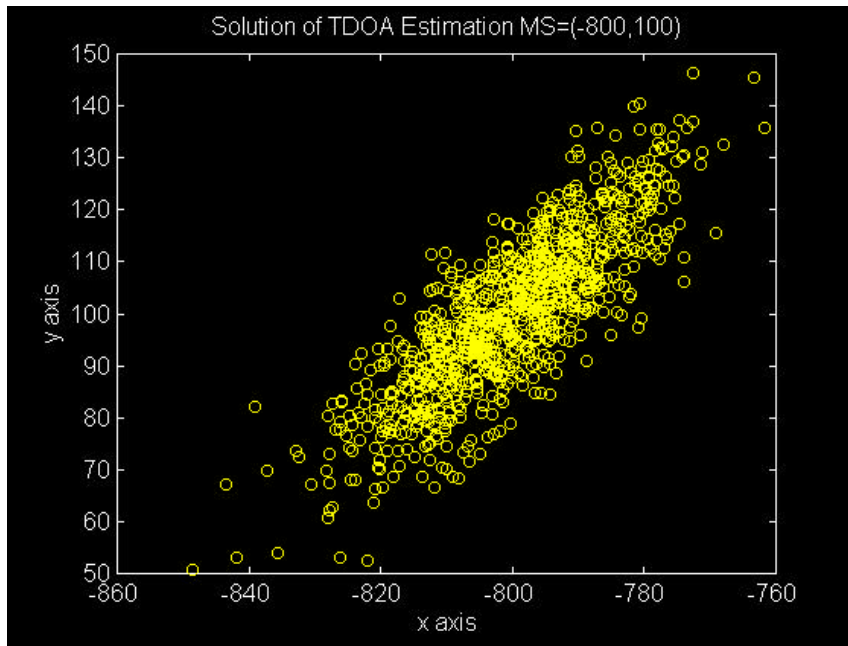
(6.2)

, Shadow
 , MS , BS
 ,
 10 m 가 가 ,
 TDOA 가 TDOA
 .
 가 . Q $100/c^2$
 0 가 .
 (- 800,100) .
 (6.17) B
 (6.15), (6.26), (6.30) .
 가 .

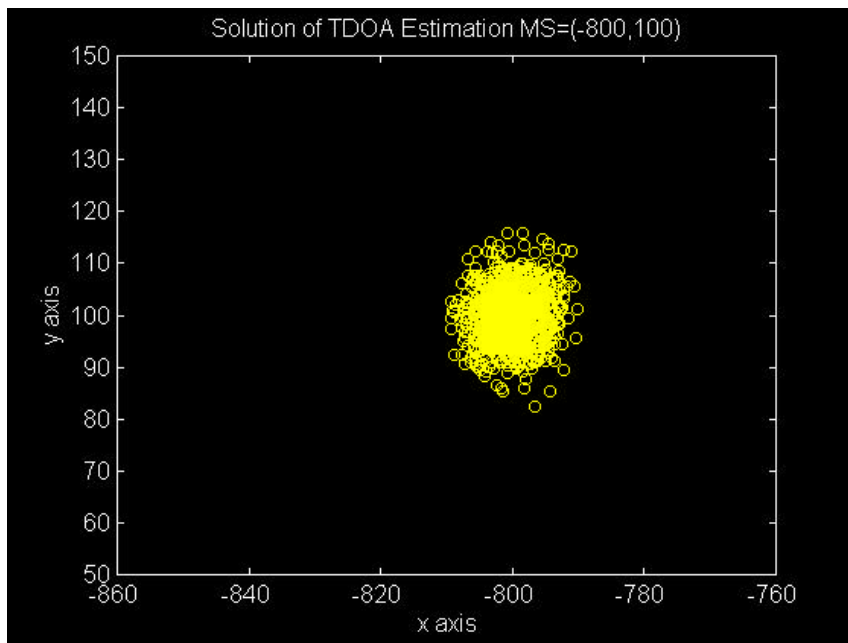
$$\text{MSE} = E[(x - x^0)^2 + (y - y^0)^2] \quad (6.37)$$
 1000 . 가 4 BS1,
 BS2, BS3, BS4 가
 .
 (6.2) CRLB
 . (6.2) 가
 . 가 5 6
 가 6 가
 가
 (6.3) 가 4
 (6.4) 가 9
 . 가

(6.2)

	4	5	6	7	8	9
MSE	387.5453	74.0032	74.0289	59.6217	45.7409	37.5847
CRLB	376.5798	73.6071	73.6067	58.5163	46.0357	37.4123



(6.3) 가 4



(6.4) 가 9

.

가 가

.

causality (linear regression) (moving average) smoothing [54].

.

1

(dB)

α

.

i

z_i

x

$d_i = \|x - z_i\|$

z_i

$x \in R^2$

.

$x = (x_1, x_2)^T$, $z_i = (u_i, v_i)^T$

i

.

가 $cd_i^{-\alpha}$

,

d_i i

, c

, $\alpha \geq 2$

.

x

i

$s_i(x)$

(7.1)

$$s_i = c[d_i(x)]^{-\alpha} \tag{7.1}$$

$$\gamma_i(t), \quad i = 1, 2, \cdots, n,$$

$$\gamma_i(t)$$

$$\delta_i(t), \quad \left[\frac{\gamma_i(t)}{c}\right]^\alpha = \delta_i(t) \tag{7.1}$$

$$\hat{x}(t) \tag{7.2}$$

$$\arg \min_x [f(x) = \sum_{i=1}^n [d_i(x) - \delta_i(t)]^2] \quad \text{over } x \in \mathbb{R}^2 \tag{7.2}$$

$$\hat{x}(t) \tag{7.2}$$

$$x_{k+1} = x_k - H_f^{-1}(x_k) \nabla f(x_k), \quad k \in I \tag{7.3}$$

$$f(x) \quad \mathcal{I} \vdash \quad x \tag{Derivative}$$

$$\nabla f(x) \tag{7.4}$$

$$\nabla f(x) = 2 \sum_{i=0}^n \frac{d_i(x) - \delta_i(t)}{d_i(x)} (x - z_i) \tag{7.4}$$

$$(7.3) \quad \text{Hessian, } H_f(x) \tag{7.5}$$

$$H_f(x) = \begin{bmatrix} f_{11}(x) & f_{12}(x) \\ f_{21}(x) & f_{22}(x) \end{bmatrix} \tag{7.5}$$

$$\begin{aligned}
 f_{11}(x) &= 2 \sum_{i=0}^n \frac{\delta_i(t) (x_1 - u_i)^2}{d_i^3(x)} + \frac{d_i(x) - \delta_i(t)}{d_i(x)} \\
 f_{22}(x) &= 2 \sum_{i=0}^n \frac{\delta_i(t) (x_2 - u_i)^2}{d_i^3(x)} + \frac{d_i(x) - \delta_i(t)}{d_i(x)} \quad (7.6)
 \end{aligned}$$

$$f_{12}(x) = f_{21}(x) = 2 \sum_{i=0}^n \frac{\delta_i(t)}{d_i^3(x)} (x_1 - u_i)(x_2 - v_i)$$

$$\nabla f(x) = 0 \quad (7.3) \quad ,$$

$$. \quad t_i \quad \hat{x}(t_i) \quad (7.3)$$

가 .

smoothing

가 . , (7.3)

$$\varepsilon = 10^{-4} .$$

$$\hat{x}(t_i) = [\hat{x}_1(t_i), \hat{x}_2(t_i)]^T, \quad i = 1, \dots, m, \quad t_i$$

.

smoothing

가 .

$$t_i \quad t_j \quad j \leq i$$

.

$$a \quad \|a\| \quad 가 , \quad t_i$$

.

$$x(t_i) = a t_i + b \quad (7.7)$$

$$, \quad b \quad 가 \quad t_0 = 0$$

$$. \quad a \quad b$$

$$\hat{x}(t_i), \dots, \hat{x}(t_k) .$$

$$\arg \min_x \sum_{j=1}^k \|\hat{x}(t_j) - (at_j + b)\|^2 \quad \text{over } a, b \in \mathbb{R}^2 \quad (7.8)$$

$$a \quad b \quad (7.9) \quad [54].$$

$$\begin{aligned} \hat{a}_l &= \frac{\sum_{j=0}^k (t_j - \bar{t}) [\hat{x}_l(t_j) - \bar{x}_l]}{\sum_{j=0}^k (t_j - \bar{t})^2} \\ \hat{b}_l &= \bar{x}_l - \hat{a}_l \bar{t}, \quad l = 1, 2 \end{aligned} \quad (7.9)$$

$$\bar{t} = (1/k) \sum_{j=1}^k t_j, \quad (7.10)$$

$$\bar{x}_l = (1/k) \sum_{j=1}^k \hat{x}_l(t_j), \quad l = 1, 2. \quad (7.8) \quad (7.9)$$

$$k$$

$$5 \quad 25.$$

$$\begin{aligned} \hat{a} &= (\hat{a}_1, \hat{a}_2)^T \\ \hat{b} &= (\hat{b}_1, \hat{b}_2)^T \end{aligned} \quad (7.11)$$

$$\begin{aligned} t_i \quad t = t_i, \\ \text{(regression line)} \\ (7.12) \end{aligned}$$

$$\hat{x}(t_i) = \hat{a}(t_i)t_i + \hat{b}(t_i) \quad (7.12)$$

$$t = t_i \quad \hat{x}(t_i) \quad t_i \quad (7.13)$$

$$\hat{s}(t_i) = \hat{a}(t_i), \quad i = 1, \dots, m. \quad (7.13)$$

$$\hat{v}(t_i) = \|\hat{a}(t_i)\| = [\hat{a}_1^2(t_i) + \hat{a}_2^2(t_i)]^{1/2} \quad (7.14)$$

2

1.

(CDMA
)
(least squares
criterion)
AOA, TOA 가
TDOA
가
[55].

2.

(shadowing)

AOA TOA, TOA TDOA

.

$$i = 1, \dots, n$$

$S_i(x)$ 가 .

$$i \qquad \qquad \qquad \gamma_i(t), \quad i = 1, \dots, n$$

(7.15) .

$$\arg \min_{grid \ x} [g(x) = \sum_{i=1}^n [S_i(x) - \gamma_i(t)]^2] \quad x \in A \qquad (7.15)$$

$$\{(x, S_i(x)) ; i = 1, 2, \dots, n\}$$

.

$$n \qquad \qquad \qquad , \ x \qquad \qquad \text{(grid)}$$

$$, \ x = [x_1, x_2]^T, \qquad S_i(x) \qquad i$$

$$x \qquad \qquad \qquad . \qquad \qquad \qquad t$$

$$, \ \gamma_i(t) \qquad \qquad \text{가 가}$$

$$, \ S_i(x)$$

가 .

,

가 가 .

$$(\quad 7.1), (\quad 7.2)$$

가 .

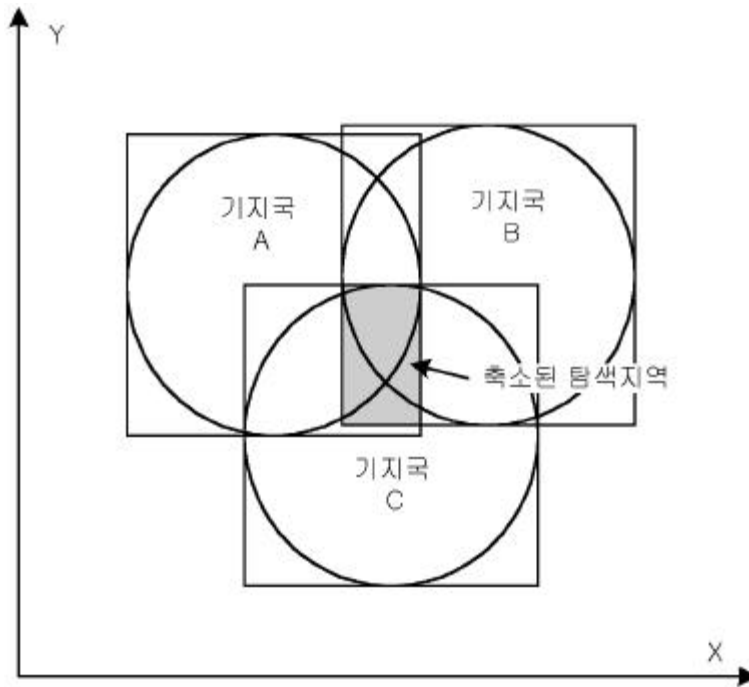
$$(\quad 7.1) \qquad \qquad \text{가} \qquad \qquad \text{가}$$

. 6

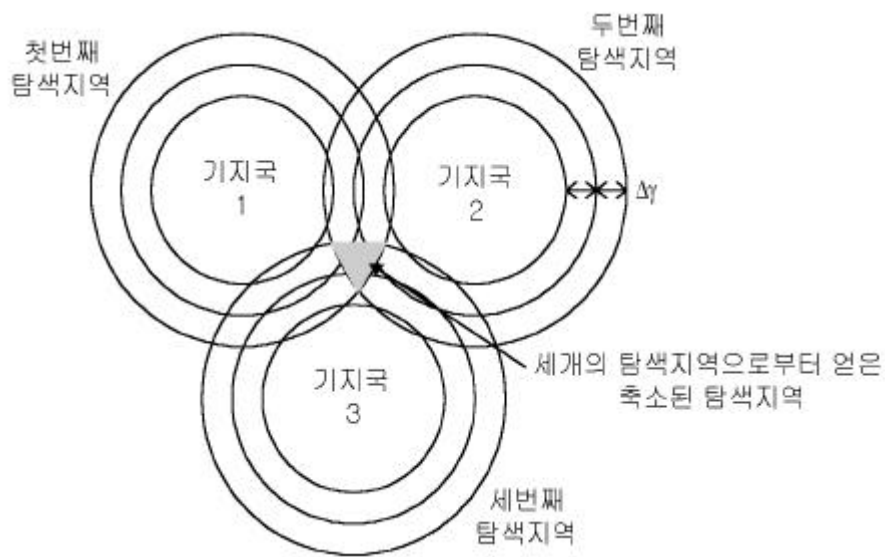
가 가

.

$$. (\quad 7.1)$$



(7.1)



(7.2)

(7.2) 가

가 . 가
 , $\{x, S_i(x)\}$ 가

non- stationarity,

(7.16) , $\Delta\gamma$

$$S_i = \{x | \gamma_i(t) - \Delta\gamma \leq S_i(x) \leq \gamma_i(t) + \Delta\gamma\}, \quad i = 1, 2, \dots, n \quad (7.16)$$

(7.17) (intersection)

$$\{x_k\}_1^N = \bigcap_{i=1}^n S_i \tag{7.17}$$

(7.18)

$$\arg \min_z [f(z) = \sum_{k=1}^N (x_k - z)^2] \tag{7.18}$$

가 (linear regression)

3

가

1.

가

[56].

140 MHz

1500 MHz

$$\begin{aligned} L_{50}(urban)(dB) = & 69.55 + 26.16 \log_{10}(f_c) - 13.82 \log_{10}(h_t) \\ & - a(h_r) + [44.9 - 6.55 \log_{10}(h_t)] \log_{10}(d) \end{aligned} \tag{7.19}$$

, f_c MHz, h_t , h_r

, d km

, $a(h_r)$.

$$a(h_r) = (1.1 \log_{10}(f_c) - 0.7)h_r - (1.56 \log_{10}(f_c) - 0.8) \quad (7.20)$$

900 MHz 10 m,

1m 가 .

$$(7.20)$$

$$(7.21) \quad .$$

$$L_{50}(dB) = L_{50}(urban) - 2[\log_{10}(f_c/28)]^2 - 5.4 \quad (7.21)$$

,

$$E_b/N_0 \quad 0$$

가 .

$$\text{SNR} \quad E_b/N_0$$

. , E_b , N_0

$$(7.22) \quad .$$

$$E_b = P_s T_{bit} \quad (7.22)$$

, T_{bit} , P_s .

Pseudo- Noise(PN) N

$$N_s \quad . \quad N_0/2$$

AWGN 가 ,

$$(7.23) \quad .$$

$$\sigma^2 = \frac{N_0}{2} \quad (7.23)$$

가 ,

.

$$\sigma^2 = \frac{A^2 N N_s}{2 E_b / N_0} \quad (7.24)$$

, A . $A = 1$.
 E_b / N_0 .
 (7.25) .

$$\sigma_n^2 = \frac{N N_s}{2 E_b / N_0} \quad (7.25)$$

(7.25) 0 가
 가 .

가.

1 km 6
 .
 900 MHz 10 m,
 1 m 가 .

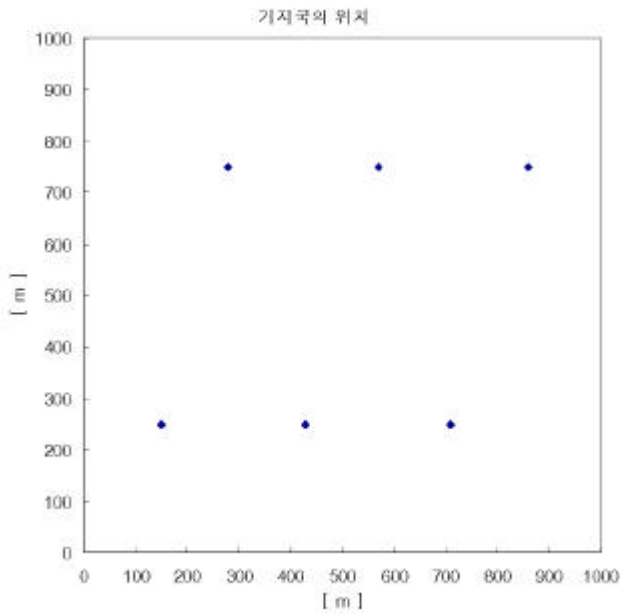
⑤ MSC(Mobile Switching Center)
 MSC Traffic Channel Control Channel 가
 4 MSC
 가
 가 가

⑥ (7.1)

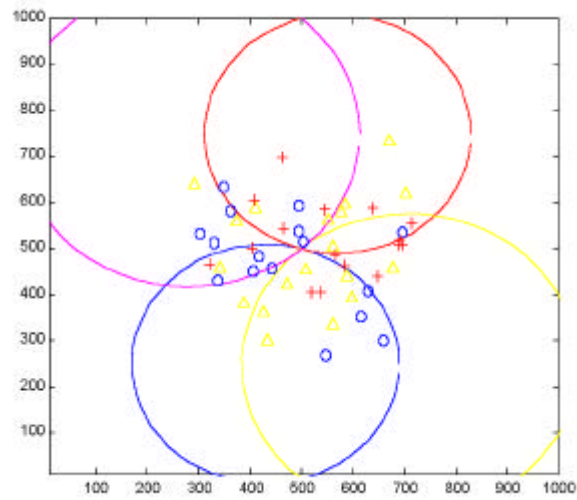
2.

(7.1)

, (7.3) ,
‘●’ .



(7.3)



(7.4)

가 4

,

4

.

가

(7.4)

(7.1)

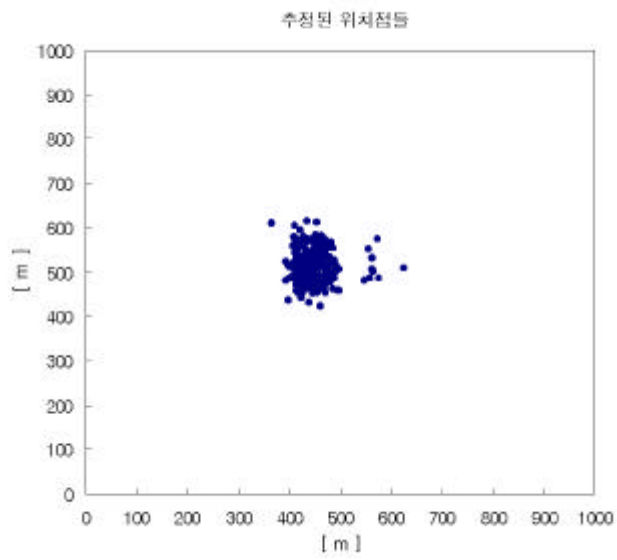
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