

Collision Avoidance for Future Operation

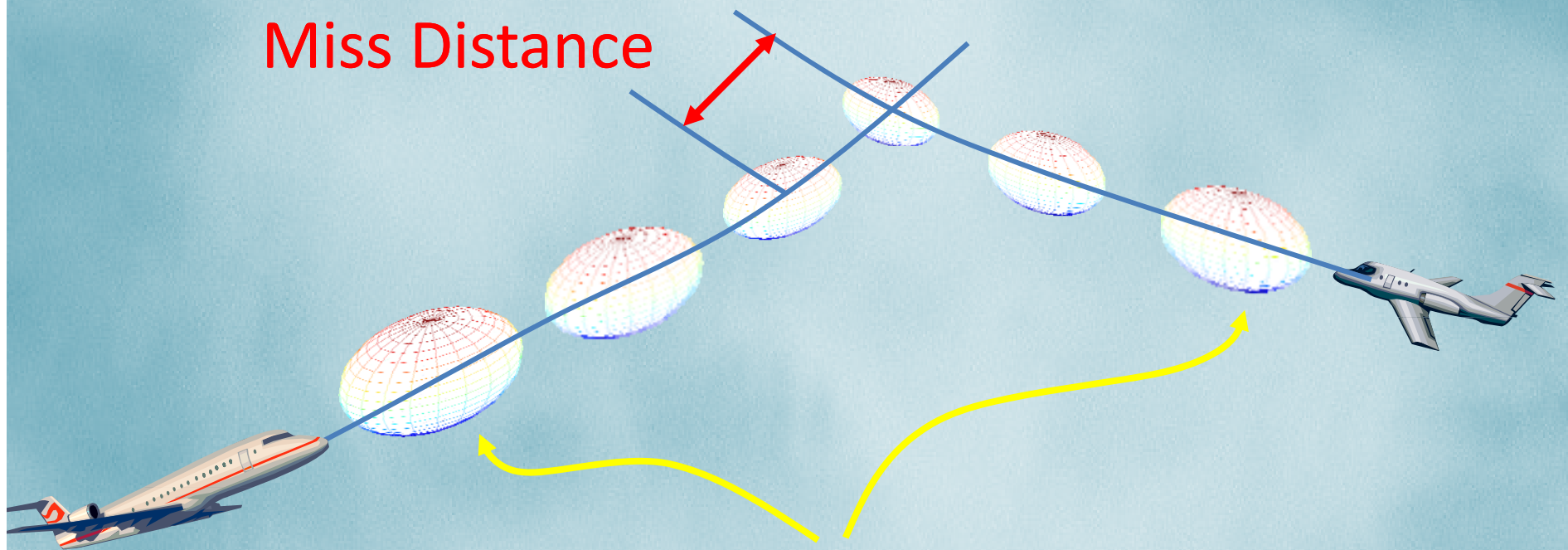
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Position Only – Perfect Velocity

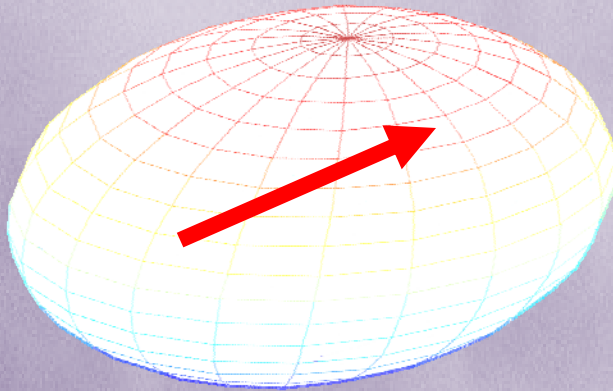


Current-Time Protection Volume

Note: only relative position and relative velocity matter

Position Predicted into the Future

Total error = Position error + $\Delta T \times$ Velocity error
Within error ellipsoid, position can change rapidly!



Position error is bounded
Velocity error is unbounded

Example:

Position error = 100 m

Velocity error = 5 m/s

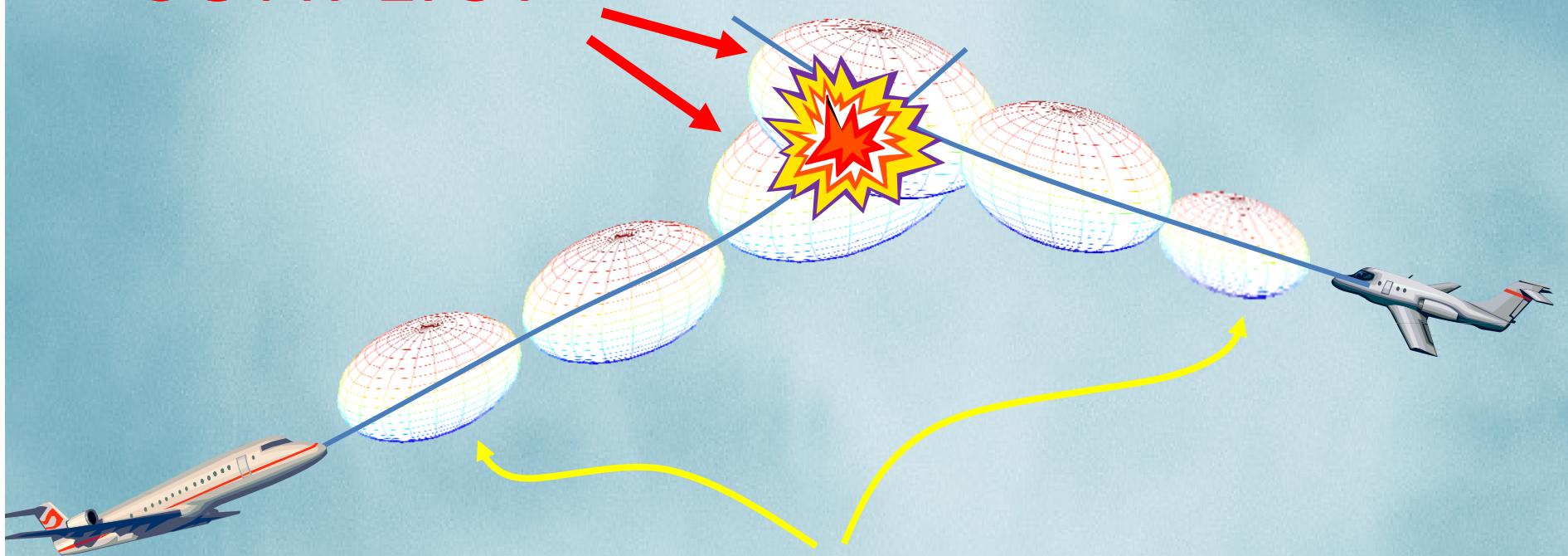
After 60 seconds:

Total error = 400 m

RAIM protection levels
are not sufficient

Position and Velocity Error

CONFLICT



Current-Time Protection Volume

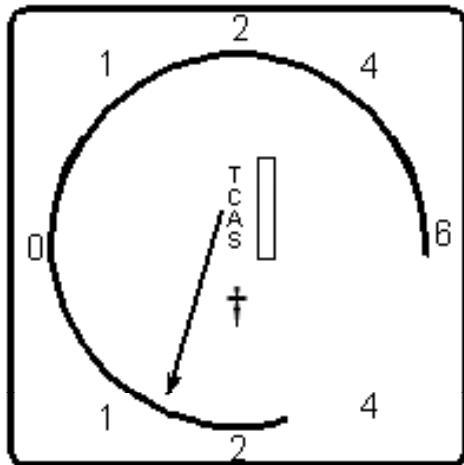
Problem and Solution

- Position broadcast alone is not sufficient without velocity integrity bounds
 - Change in satellite selection causes velocity error which can be hidden by position smoothing
 - Ionosphere front causes velocity error
 - RAIM doesn't detect 5 m/s ramp errors fast enough
- Broadcast raw measurement data:
 - Pseudoranges and carrier phase
 - Calculate relative position and velocity from raw measurement data: common errors cancel

ADS-B

- Automatic Dependent Surveillance –Broadcast (ADS-B) forms an important part of NextGen.
- Near-future applications:
 - Reduced separation,
 - airport situational awareness,
 - final approach runway occupancy,
 - enhanced visual approaches and acquisition,
 - merging and spacing of approach traffic,
 - optimized profile descent,
 - etc.

TCAS Symbology

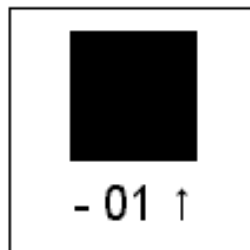
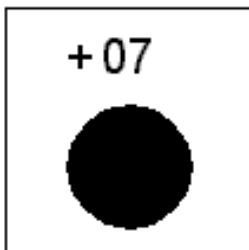
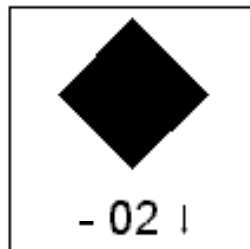
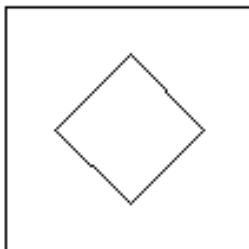


Vertical Speed Scale (RED/GREEN)
 Segments $\pm .2, .5, 1, 1.5, 2, 2.5, 6$ Kfpm

Preventive/Corrective RA; if latter -
 Fly to keep VSI needle in GREEN

Combine RA with TA Display

Own-Aircraft symbol on vertical \mathcal{E}



◇ Nonintruding traffic; alt unknown

◆ Proximity traffic (WHITE, CYAN);
 200 ft below, Descending

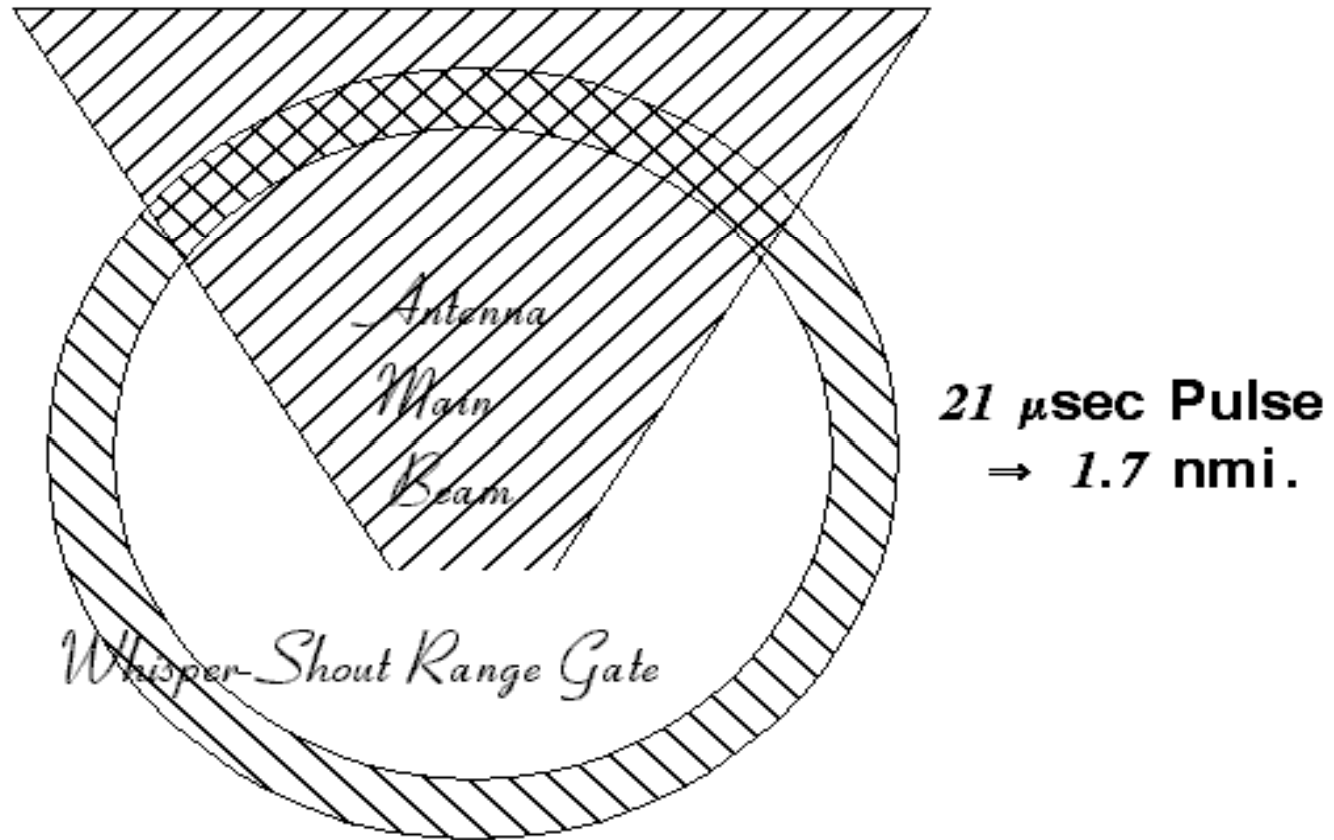
● TA (intruder - AMBER);

700 ft above, "Level" < 500 fpm

■ TA (threat - RED);

100 ft below, Ascending

Range & Alt "OK", Azimuth *CRUDE*



INTERSECTION :

2 Spheres with Horizontal Plane

SECTOR - Antenna Main Lobe

SPHERE RADII : Range

Distance Limits via Interrogation / Suppression

AIRPORT SURFACE SURVEILLANCE PLAN

Present:

Separate provisions, detached from TCAS

Takeoff, taxi instruction amassed visually (tower controller)

ASDE = Airport Surface Detection Equipment:

Radar reflections, no ID, range & LOS (resolution)

About 30 busy airports only

Lincoln Labs 1994 (Nat'l Technical Meeting + ION-GPS):

Mode S Data Link for ADS-B

(Automatic Dependent Surveillance Broadcast)

1-Hz auto (not response to interrogation)

Extended Squitter format

ID included

Lat + Long + Motion + Hdg - occupy 48 bits

DGPS (*if* available on user equipment) \Rightarrow *either*

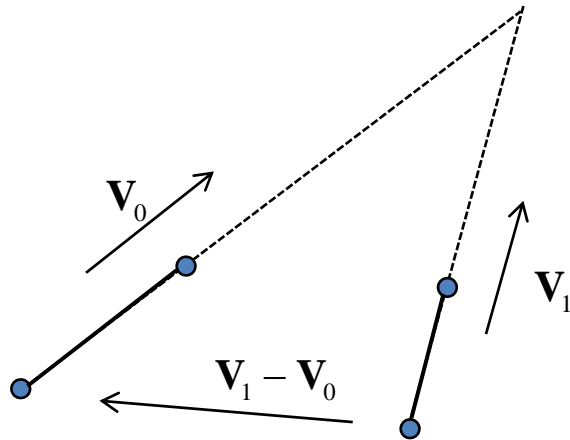
WAAS

or 1030 MHz LAAS transmission

Collision Course

\mathbf{R} = Instantaneous Separation Vector

\mathbf{V} = Instantaneous Relative Velocity Vector $= \mathbf{V}_1 - \mathbf{V}_0$



$$\text{LOS Rate} = \frac{\mathbf{R} \times \mathbf{V}}{|\mathbf{R}|^2}$$

In general, time-varying

$\mathbf{R} \parallel \mathbf{V} \Rightarrow$ Collision course

- **Conditions at close range:**

- Changing geometry,
- Changing speeds,
- TTG not dependable.

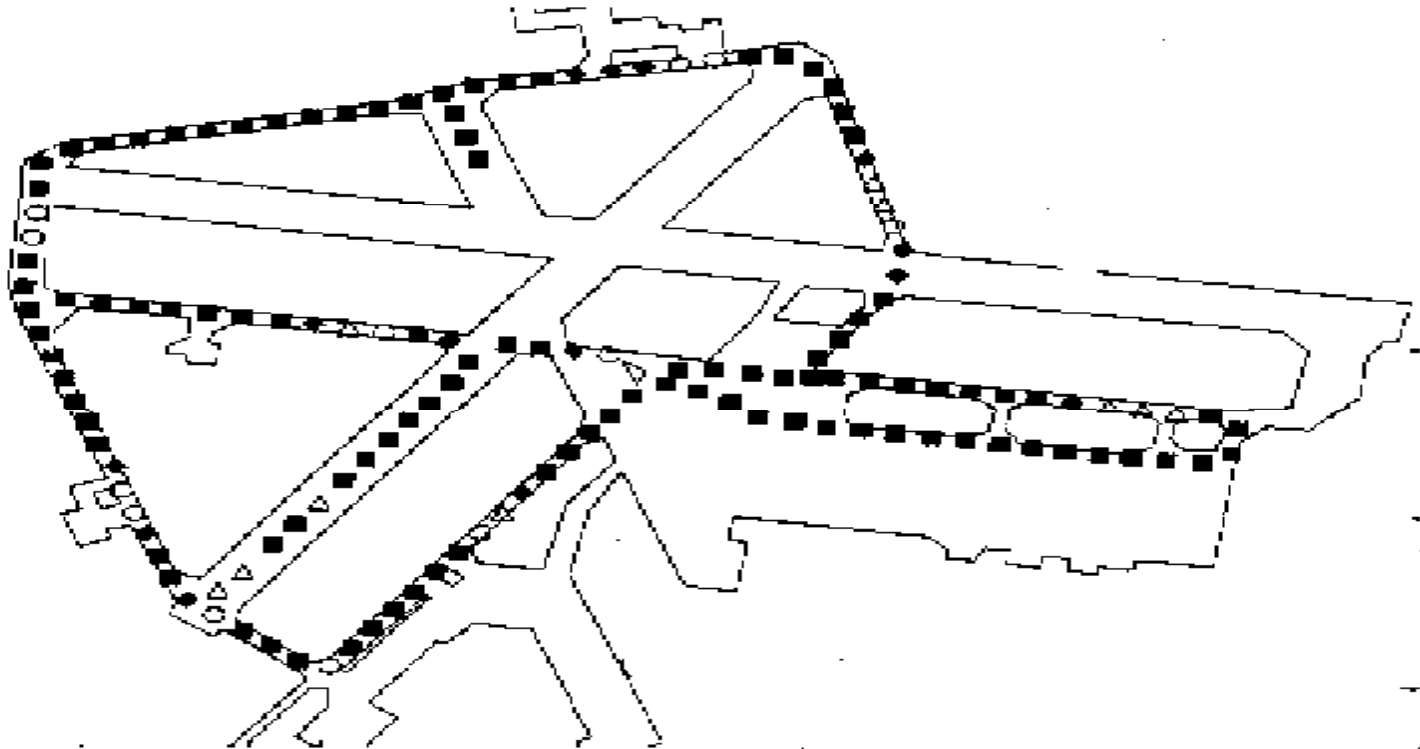
$$\text{TTG} = \frac{|\mathbf{R}|}{(\text{Range rate})} :$$

Valid IFF LOS rate = 0

LINCOLN LAB SUCCESSFUL TEST

Transmission of GPS Coordinates

LOGAN Airport , 1990s



Lincoln Labs 1994 Message Format

- Add to the extant 56-bit Mode-S Message length – After control between address and parity

Airborne

Type	Turn	Spare	Baro alt	Time	Lat	Lon
------	------	-------	----------	------	-----	-----

17 bits each for Latitude and Longitude

14 additional bits for Altitude, Turn, Spare

Ground

Type	Spare	Movement	Heading	Time	Lat	Lon
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17 bits each for Latitude and Longitude

7 bits each for Heading and Movement

48 total bits for Position and Dynamics

Transmitted Coordinates

- Data acceptance conditional (quality),
- Loss of partial data,
- Correlation between coordinate errors,
- Unequal error amounts in different directions,
- Non-uniform coordinate error statistics,
- Non-uniform coordinate error sensitivities,
- Non-uniform data.

Solution: Transmit GPS pseudoranges.

ALTERNATIVE METHOD

Integrate

Next-generation TCAS

Airport surface surveillance

Extended Squitter format :

Change only 48 message bits

Pseudorange modulo 2^N

Examples (LSB = 1 meter) :

$N = 12$ (surface, > 4 km) 4 SVs

$N = 16$ (air, > 65 km) 3 SVs

Scale for Long Range (LSB = 4 meter) :

$N = 16$ (air, > 260 km) 3 SVs

Rereference time to nearest GPS second (Lincoln Labs)

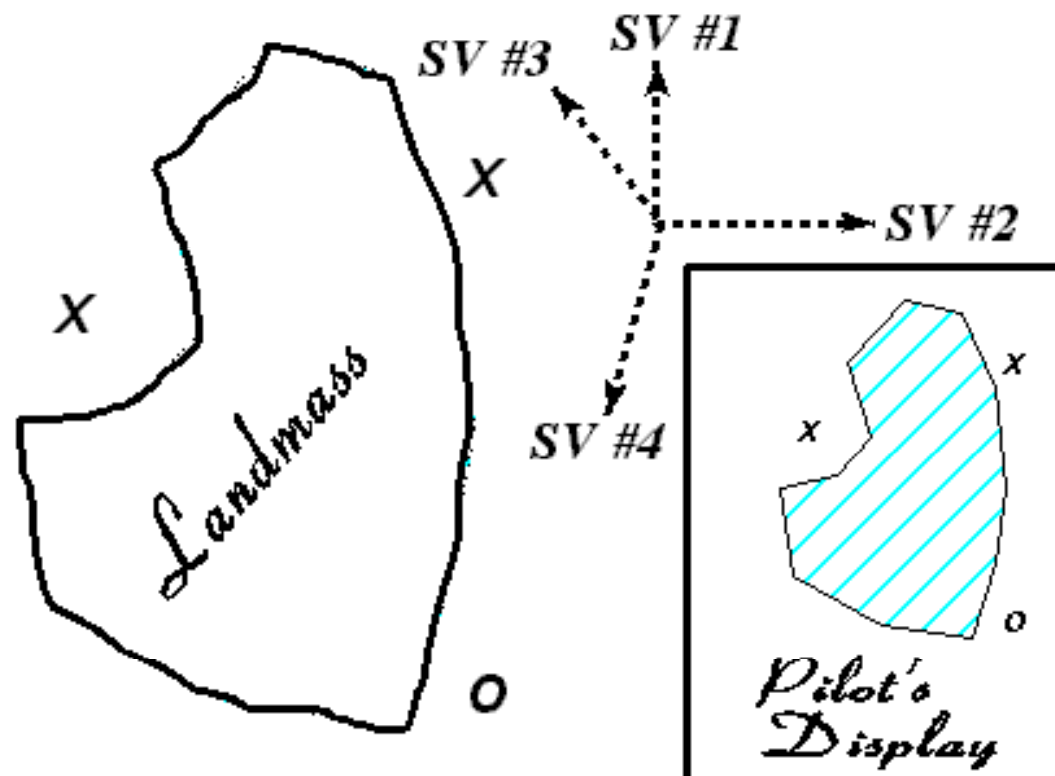
Rereference pseudorange to *CG* (cancel rotation effects)

Residual test \Rightarrow No SV-ID req'd

Correct TROPO only (nontrivial)

Other major errors cancel

ACCURATE TRACK PLACEMENT



Nav error affects *Landmass* if shown on Pilot's Display

Location Up / Down, Left / Right

Azimuth Rotation

Altitude Scaling

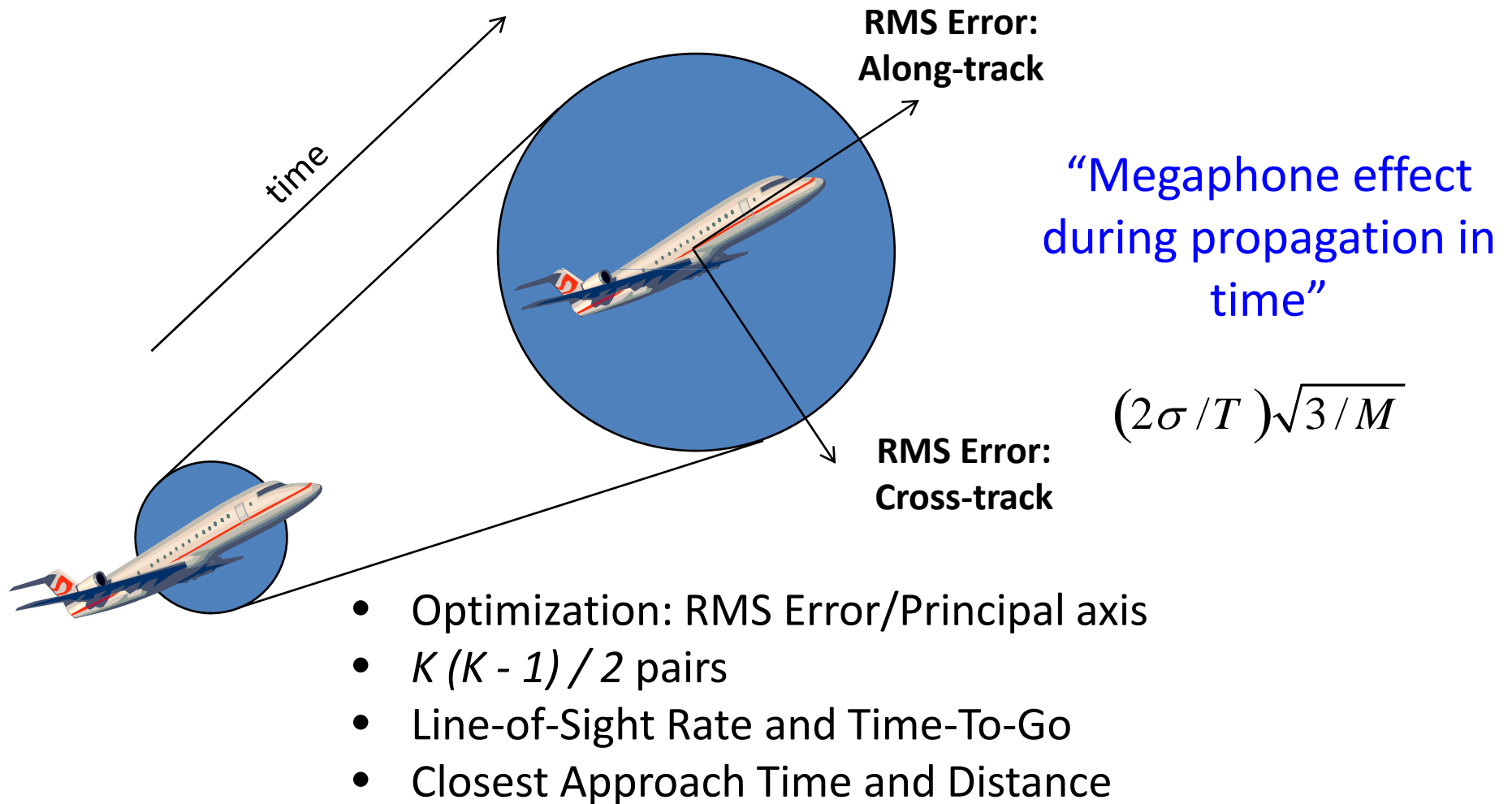
but *Tracked Objects* ('X' w.r.t. 'O') remain correct.

Transmitting Measurements

Advantages

- Major accuracy improvement,
- Increased observability,
- Independent of Datum Reference,
- Intrinsic quality indication (Covariance matrix),
- Coordinates always computable,
- Data always usable if deemed valid,
- Correlations always accounted for,
- Optimum weighting,
- Uncorrected C/A fully adequate
 - 1030 MHz COMM savings
- Pseudorange double differences,
- Carrier sequential differences,
- Integrity capability.

The Importance of Velocity Estimates



Closest Approach Time and Distance

- Form every possible vehicle pair,
- Subtract position vectors $\Rightarrow \mathbf{S}$
- Subtract velocity vectors $\Rightarrow \mathbf{U}$
- Minimum (sq) separation $(\mathbf{S} + \tau\mathbf{U}) \cdot (\mathbf{S} + \tau\mathbf{U})$

$$\frac{d}{dt}(\mathbf{S} + \tau\mathbf{U}) \cdot (\mathbf{S} + \tau\mathbf{U}) = 0 \Rightarrow$$

$$2\mathbf{U} \cdot \mathbf{S} + 2\tau\mathbf{U} \cdot \mathbf{U} = 0 \Rightarrow \tau = -\frac{\mathbf{U} \cdot \mathbf{S}}{|\mathbf{U}|^2} = -\frac{\mathbf{u} \cdot \mathbf{S}}{|\mathbf{U}|} \quad \leftarrow$$

$$\mathbf{S} + \left(-\frac{\mathbf{u} \cdot \mathbf{S}}{|\mathbf{U}|}\right)\mathbf{U} = \mathbf{S} - (\mathbf{u} \cdot \mathbf{S})\frac{\mathbf{U}}{|\mathbf{U}|^2} = \mathbf{S} - (\mathbf{u} \cdot \mathbf{S})\frac{\mathbf{u}}{|\mathbf{u}|^2} = \mathbf{S} - \frac{(\mathbf{u} \cdot \mathbf{S})\mathbf{u}}{|\mathbf{u}|^2} = \frac{|\mathbf{S} \times \mathbf{u}|^2}{|\mathbf{u}|^2} \quad \leftarrow$$

RCVRS SEPARATED by SHORT BASELINE

↳ Direction of Vector S from SV to mid-baseline

Ref. Location of
RCVR #0 (Origin)

Offset Location
of RCVR # 1



Notation :

$$\mathbf{1}_S = \mathbf{S}/|\mathbf{S}|$$

$B_0 B_1$ =RCVR biases

$C_0 C_1 C_S$ =Clock errors

M =Multipath

N =Noise

Q =Quantiz.

Equations for pseudoranges - from -

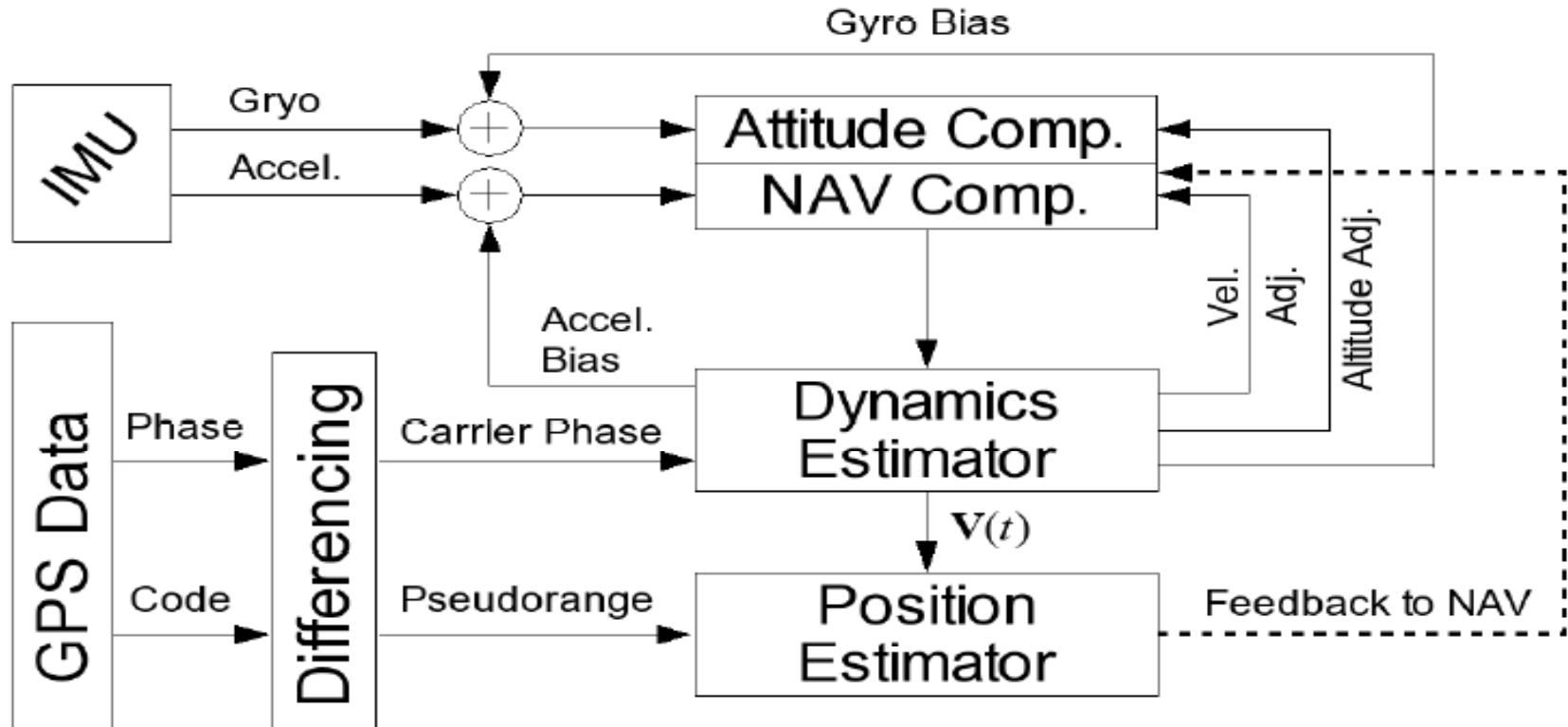
$$\text{OFFSET: } (\mathbf{R} - \mathbf{S}) \cdot \mathbf{1}_S + \text{IONO} + \text{TROPO} + B_1 + C_1 - C_S + M_1 + N_1 + Q_1$$

$$\text{ORIGIN: } (-\mathbf{S}) \cdot \mathbf{1}_S + \text{IONO} + \text{TROPO} + B_0 + C_0 - C_S + M_0 + N_0 + Q_0$$

$$\text{DIFF: } \mathbf{R} \cdot \mathbf{1}_S + B + C + M + N + Q$$

- $\Delta(\text{IONO}) \approx 0$
- If $\Delta(\text{TROPO}) \neq 0$ adjust for altitude, wet / dry
- Eliminate B & C by subtracting DIFFs from two SVs
- Sync requirements \Rightarrow knowledge (not control) of meas. timing

ADVANCED METHODOLOGY



FLIGHT RESULTS

$\delta \nabla Y$	a	b	$h \cdot \omega_s \times R_{m-1}$	$h \int V d\tau$	Residual
-359.71	818.26	-245.14	-174.79	-38.63	-0.01
-169.81	57.75	-245.14	303.22	53.97	-0.01
-31.75	402.64	-245.14	-110.76	-14.99	0.00
416.93	-309.48	-245.14	120.14	17.55	-0.01
-271.26	651.70	-245.14	-116.03	-19.27	0.00
74.17	357.41	-245.14	-160.37	-26.07	-0.01

Benefits

- **Efficiency**
 - Computational economy (UD)
 - No new HDWE or provisions
- **Accuracy**
 - Double differences, Kalman Filter
- **Less sensitivity to interference**
 - No corrections needed
 - Partial fixes utilized
- **Consistency**
 - Optimal path estimates for all participants
- **Rigor**
 - Closest approach
 - Covariances
- **Thoroughness**
 - Every possible pair