A Linear Altitude Rule for Safer and More Efficient Enroute Air Traffic

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(expanded version)

Outline

- Background and Motivation
- Collision Probability Analysis
- Monte Carlo Simulation Methods
- Collision Rates and Closing Speeds
- Implications for Conflict Resolution
- Conflict Rates
- Conclusion

The Main Point

Current enroute altitude rules are not as fail-safe or as fault-tolerant as they could be. Without a foundation of fail-safe and fault-tolerant air traffic rules, safety can be maintained only at the expense of efficiency and capacity.

Fail-Safe Design

Safety is incorporated into the basic design and depends as little as possible on complicated monitoring and backup systems. Examples:

- nuclear power control rods
- railroad crossing gates
- elevator emergency brakes

Definitions of Altitude Rules

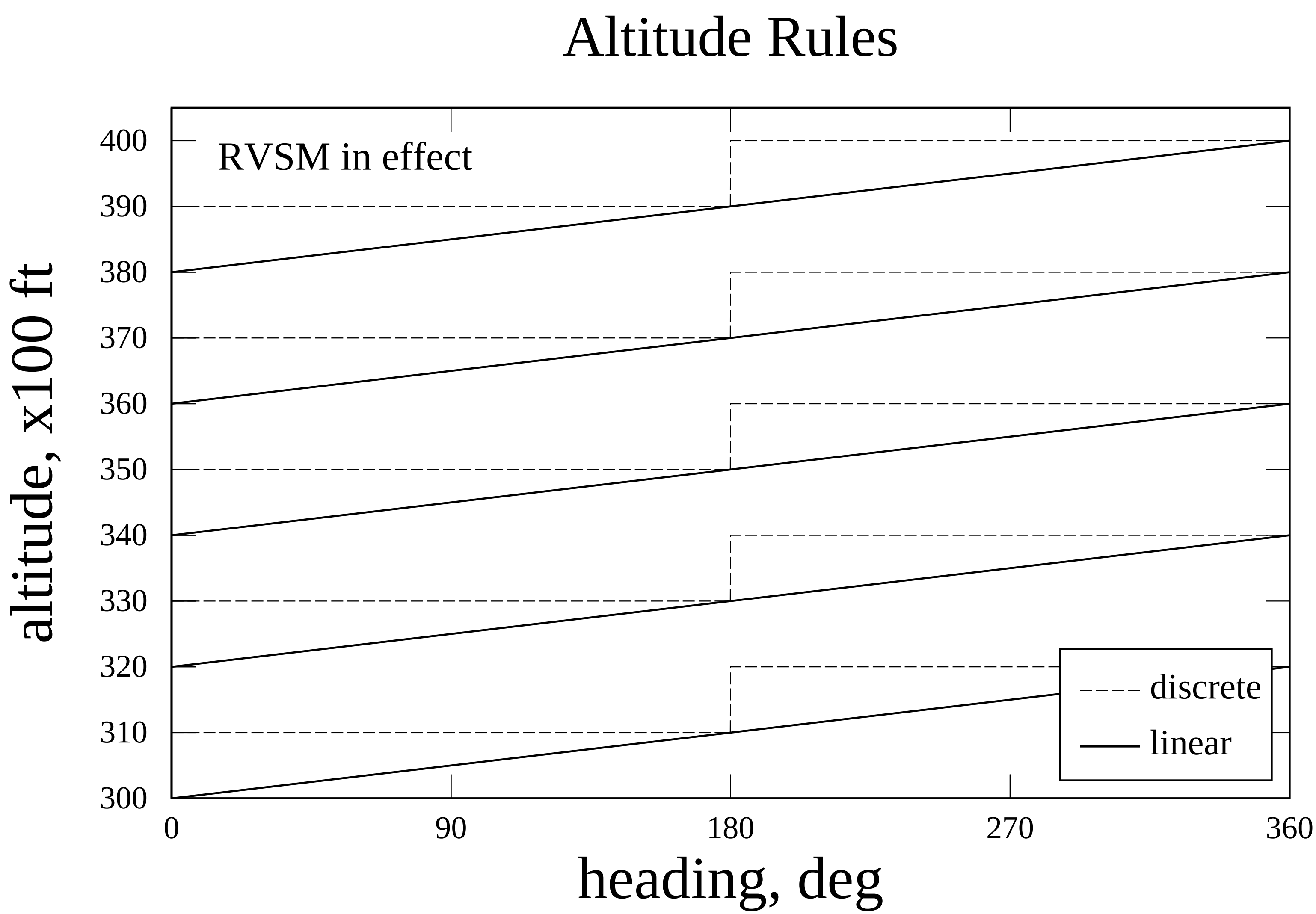
- **Discrete**: current designation of cruise altitudes in discrete steps of 1000 (or 2000) ft
- **Linear**: proposed designation of cruise altitudes as a linear function of heading or course (Patlovany, 1997)

Reduced Vertical Separation Minimum

RVSM reduces the vertical separation standard between FL290-410 from 2000 ft to 1000 ft

- Doubles enroute capacity from FL290-410
- Allows cruising closer to optimal altitude
- Is driving improvements in baro-altimetry

- Already in effect over large oceanic regions
- Scheduled for Europe in 2002
- Expected in US by 2005



Altitude Rules
RVSM in effect
400
390
380
370
360
350
340
330
320
310
300
altitude, x100 ft
0
90
180
270
360
heading, deg
discrete
linear

Formulas for Altitude Rules

discrete: $A = 10\,\mathrm{int}(\psi/180 + 2i + 1)$

linear: $A = 20\,(\psi/360 + i)$

where

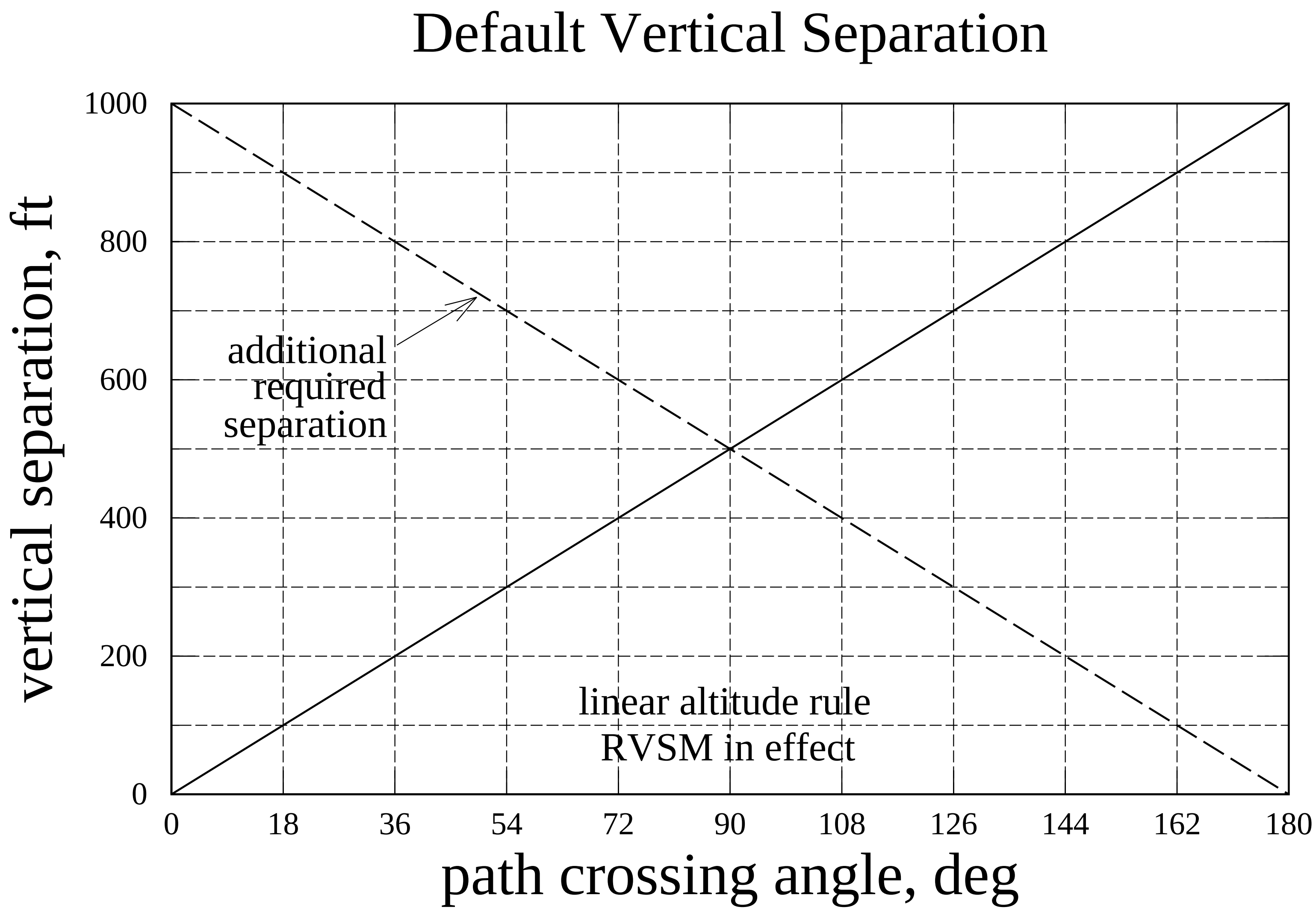
- A is altitude in units of 100 ft
- ψ is heading in degrees
- i is the "altitude cycle" integer
- "int" function is integer truncation

Altitude Offset Lookup Table

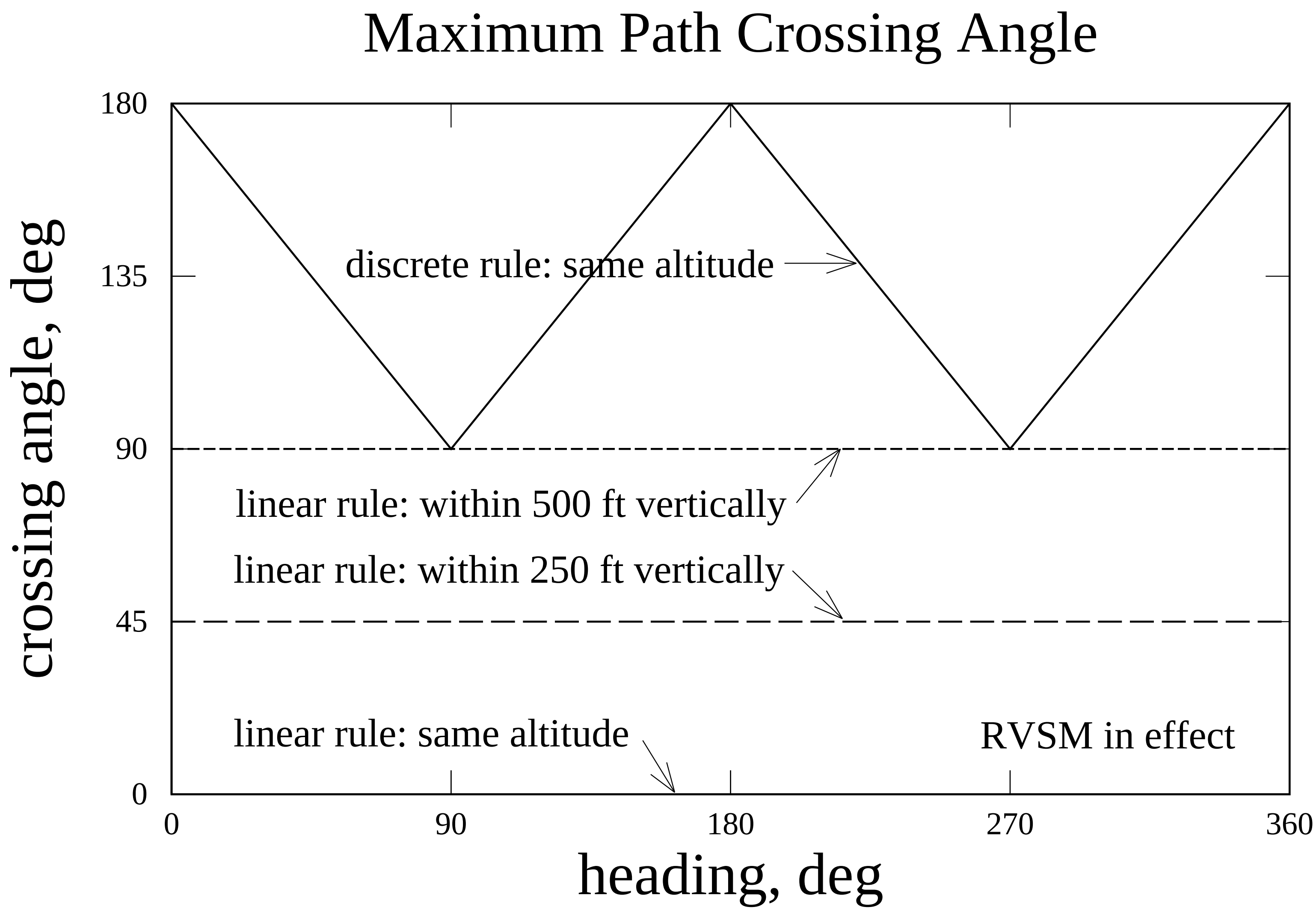
Heading	+	+	Heading
351 - 008	0	10	171 - 188
009 - 026	1	11	189 - 206
027 - 044	2	12	207 - 224
045 - 062	3	13	225 - 242
063 - 080	4	14	243 - 260
081 - 098	5	15	261 - 278
099 - 116	6	16	279 - 296
117 - 134	7	17	297 - 314
135 - 152	8	18	315 - 332
153 - 170	9	19	333 - 350

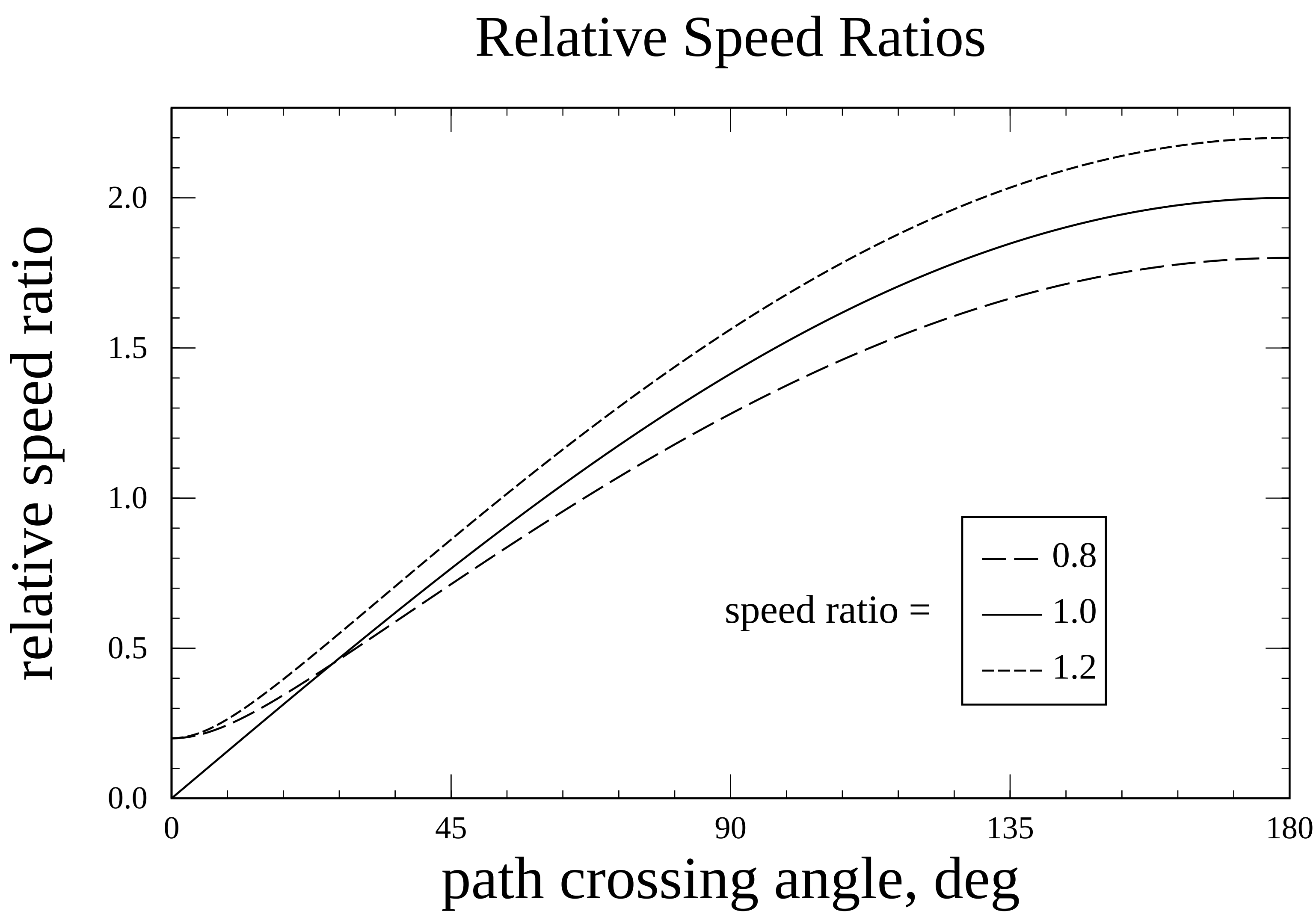
Problems with the Discrete Altitude Rule

- Most airspace unused for level flight
- Concentrates traffic at a few altitudes
- Many large-angle conflicts at same altitude
- Less Fail-Safe/Fault-Tolerant than could be
  - Inefficient static route system needed
  - Large horizontal separation needed

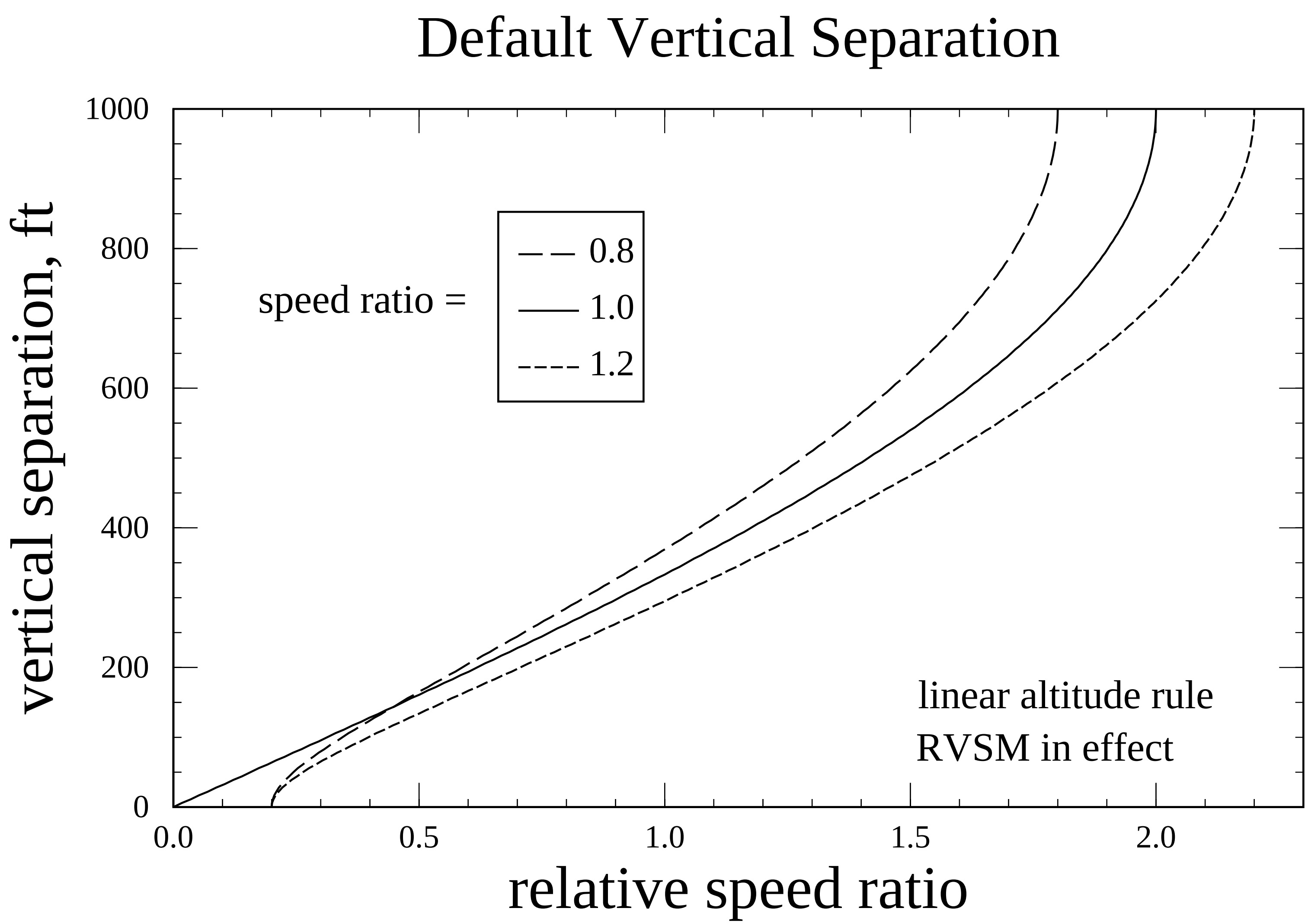


Default Vertical Separation
vertical separation, ft
1000
800
600
400
200
0
additional
required
separation
linear altitude rule
RVSM in effect
0
18
36
54
72
90
108
126
144
162
180
path crossing angle, deg


Maximum Path Crossing Angle
crossing angle, deg
heading, deg
180
135
90
45
0
0
90
180
270
360
discrete rule: same altitude
linear rule: within 500 ft vertically
linear rule: within 250 ft vertically
linear rule: same altitude
RVSM in effect



Relative Speed Ratios
relative speed ratio
2.0
1.5
1.0
0.5
0.0
0
45
90
135
180
path crossing angle, deg
speed ratio =
0.8
1.0
1.2

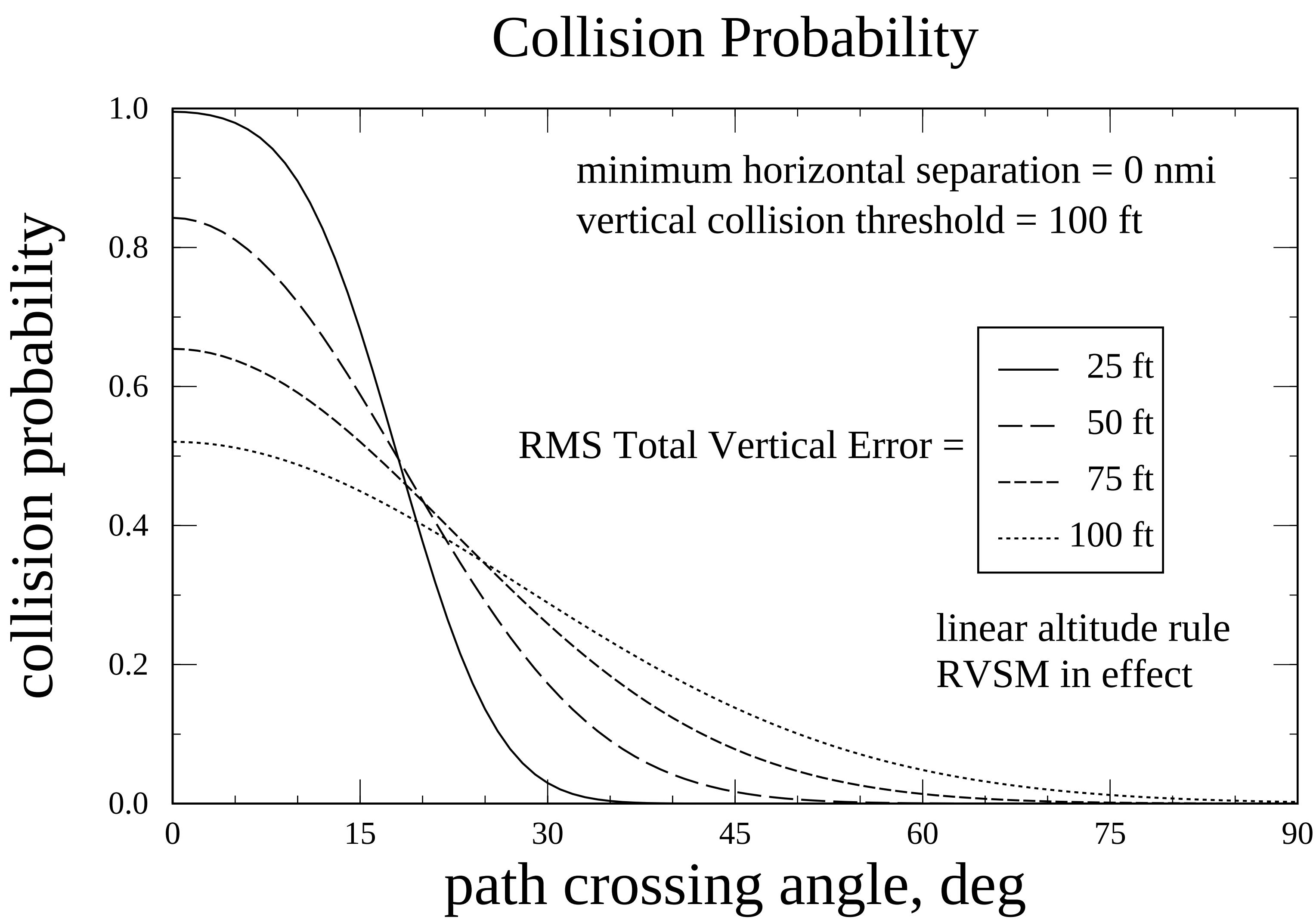


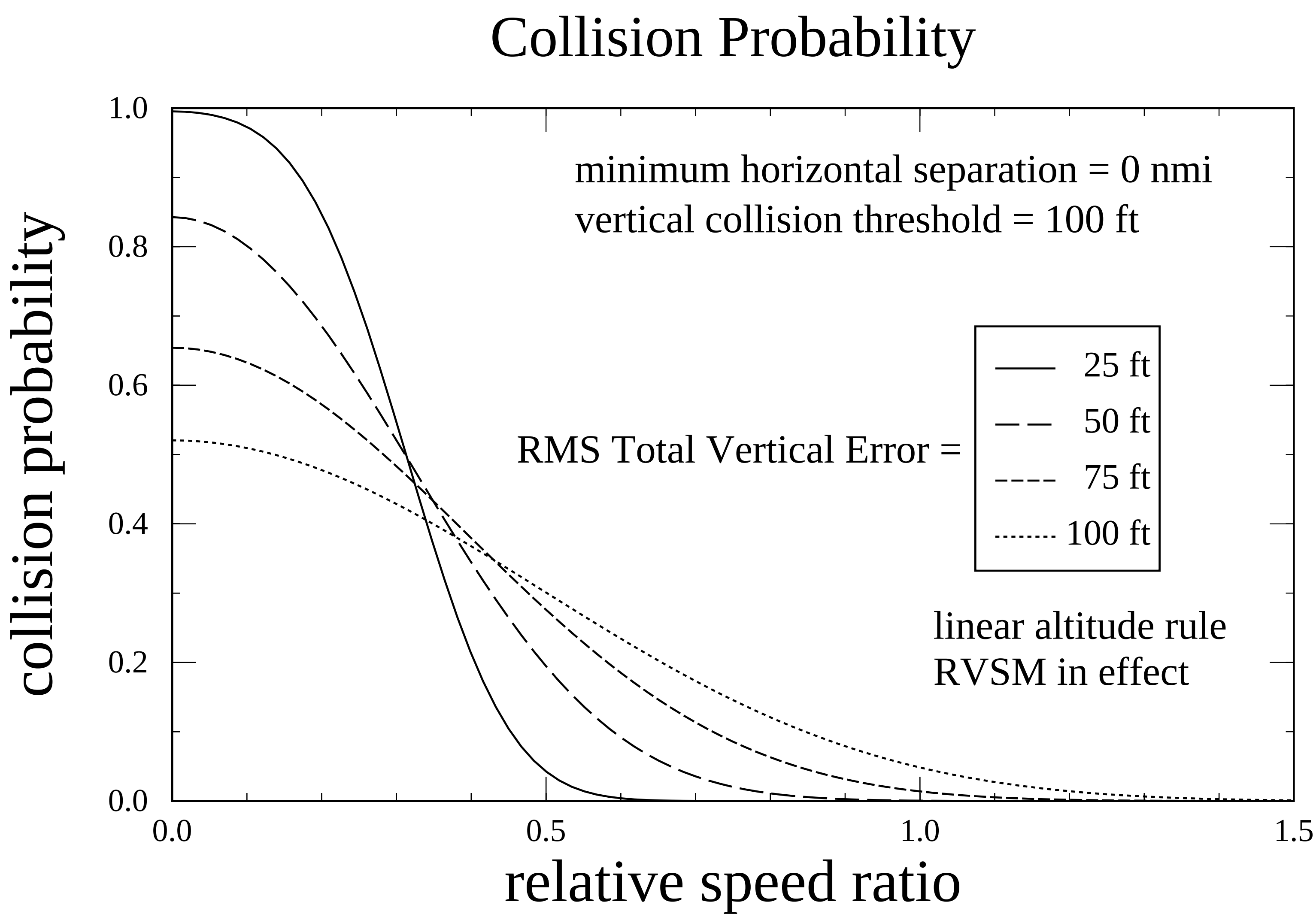
Default Vertical Separation
vertical separation, ft
relative speed ratio
1000
800
600
400
200
0
0.0
0.5
1.0
1.5
2.0
speed ratio =
0.8
1.0
1.2
linear altitude rule
RVSM in effect

Total Vertical Error

TVE is the difference between actual and assigned pressure altitude (accounts for both measurement and flight technical error)

- RMS TVE $\approx$ 50 ft for RVSM-qualified AC
- RMS TVE $<$ 25 ft with GPS/WAAS?


Collision Probability
minimum horizontal separation = 0 nmi
vertical collision threshold = 100 ft
RMS Total Vertical Error =
25 ft
50 ft
75 ft
100 ft
linear altitude rule
RVSM in effect
collision probability
1.0
0.8
0.6
0.4
0.2
0.0
0
15
30
45
60
75
90
path crossing angle, deg

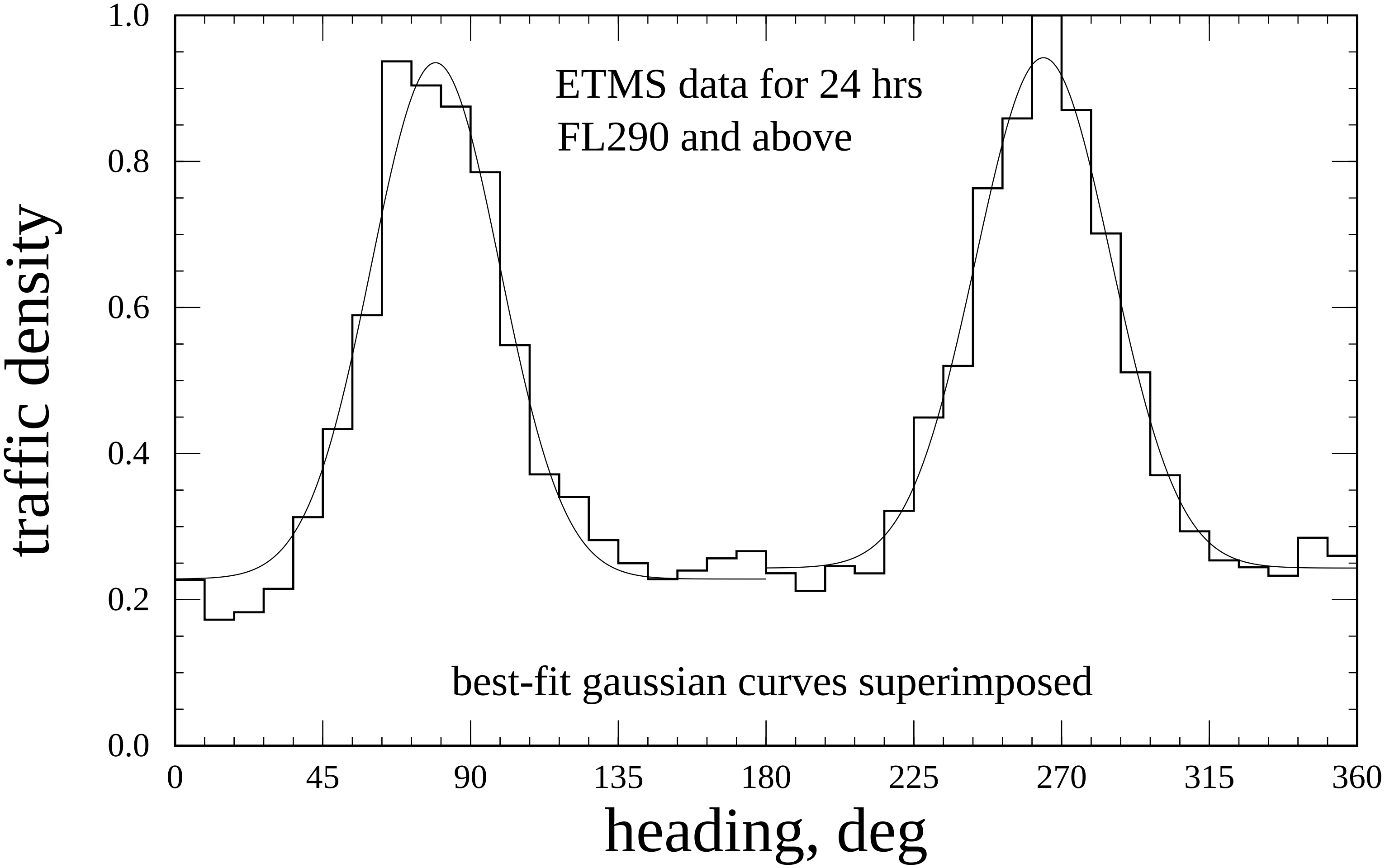


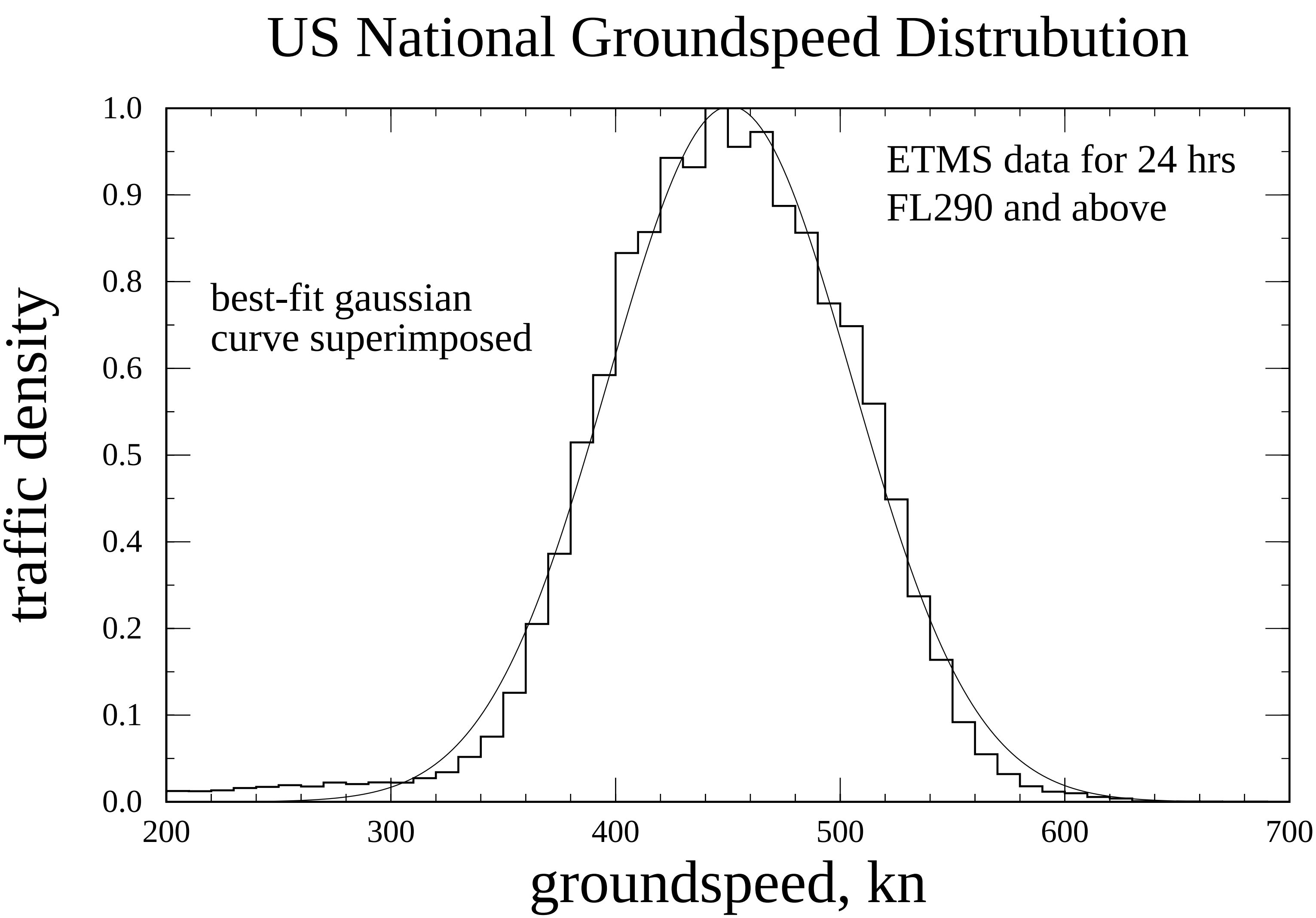
Collision Probability
collision probability
relative speed ratio
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
minimum horizontal separation = 0 nmi
vertical collision threshold = 100 ft
RMS Total Vertical Error =
25 ft
50 ft
75 ft
100 ft
linear altitude rule
RVSM in effect

Monte Carlo Simulation

- No air traffic control
- Level flight at constant velocity
- 200 aircraft in 500 x 500 nmi region
- Altitudes from FL300 to FL400
- Random horizontal positions
- Empirical heading/speed distribution
- Simulated time per run: 30 min
- 250,000 Monte Carlo runs

US National Heading Distribution




US National Groundspeed Distrubution
ETMS data for 24 hrs
FL290 and above
best-fit gaussian
curve superimposed
traffic density
groundspeed, kn
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
200
300
400
500
600
700

Collision Thresholds

collision threshold	separation	
	horizontal	vertical
minimal	200 ft	50 ft
nominal	300 ft	100 ft

- minimal: approximate size of B777
- nominal: additional buffer

Collision Rate Reduction Factors

Minimal Collision Threshold

altitude rule	RMS total vertical error			
	25 ft	50 ft	75 ft	100 ft
discrete	1.0	1.0	1.0	1.0
random	5.0	3.3	1.8	1.4
linear	33.8	13.9	5.8	4.8

- Random altitudes reduce collision rates
- Linear rule *greatly* reduces collision rates

Collision Rate Reduction Factors

Nominal Collision Threshold

altitude rule	RMS total vertical error			
	25 ft	50 ft	75 ft	100 ft
discrete	1.0	1.0	1.0	1.0
random	2.8	2.9	2.2	1.7
linear	10.3	7.9	5.6	3.8

The factors for the linear rule are not quite as high as with the minimal collision threshold

Mean Relative Speed of Collisions (kn)

Nominal Collision Threshold

altitude rule	RMS total vertical error 25 ft	50 ft	75 ft	100 ft
discrete	462	458	446	450
random	675	663	686	692
linear	109	127	164	211

- Random altitudes *increase* closing speeds
- Linear rule *greatly reduces* closing speeds

Mean Collision Speed Reduction Factors

altitude	RMS total vertical error			
rule	25 ft	50 ft	75 ft	100 ft
discrete	1.0	1.0	1.0	1.0
linear	4.2	3.6	2.7	2.1

The linear rule greatly reduces closing speeds

Horizontal Separation Standard

Depends on:

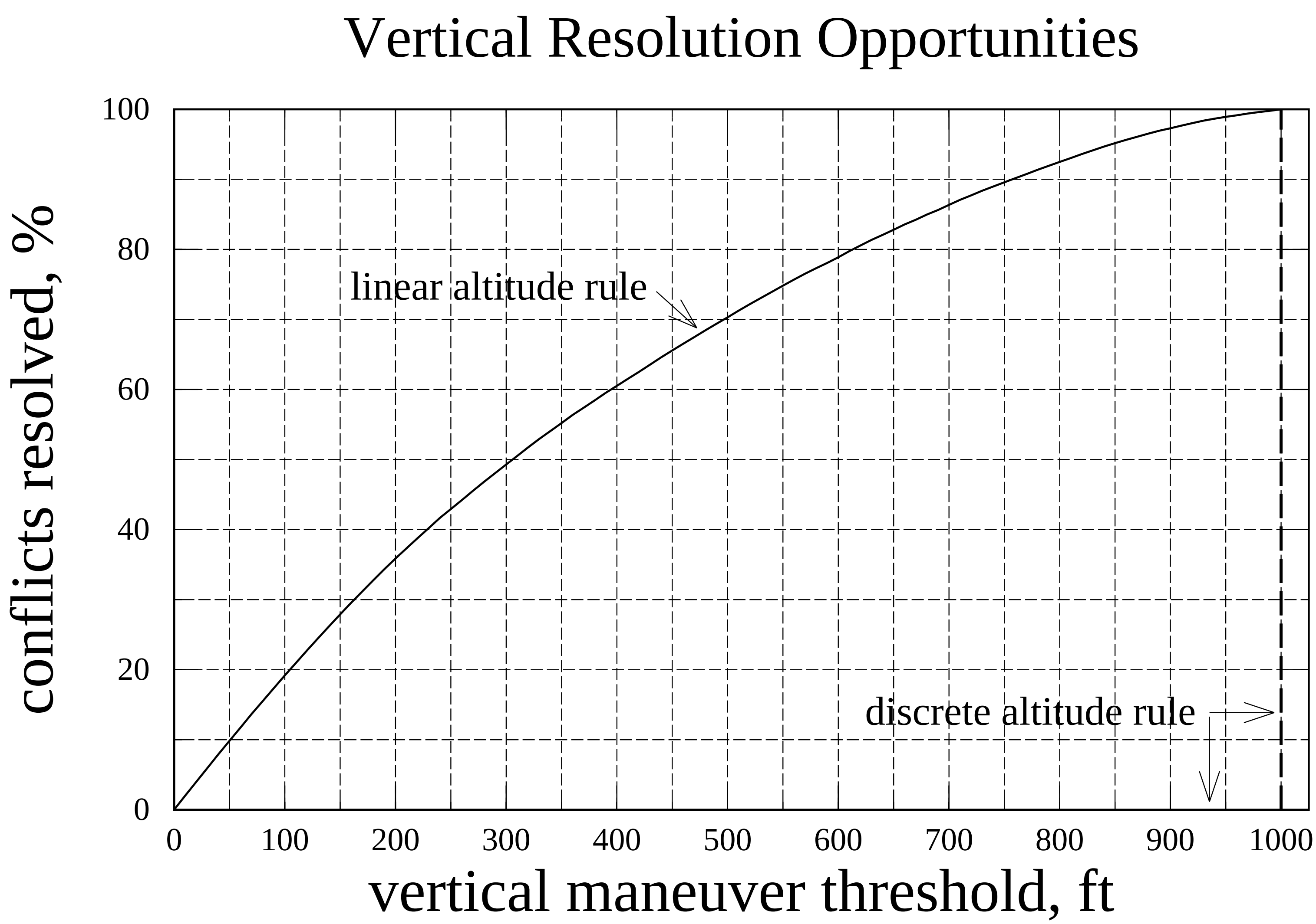
- Surveillance accuracy and reliability
  - ADS-B and GPS/WAAS revolution
- Decision support systems and tools
  - CTAS, URET, TCAS, CDTI
- Closing speeds of potential collisions
  - greatly reduced by linear altitude rule

Horizontal Separation Standard

- current enroute standard: 5 nmi
- ADS-B, GPS, multi-radar: 3 nmi?
- conflict probe, CDTI, TCAS: 2 nmi?
- linear altitude rule: 1 nmi?
  - fewer conflicts to be resolved
  - increased airspace capacity
  - improved resolution efficiency

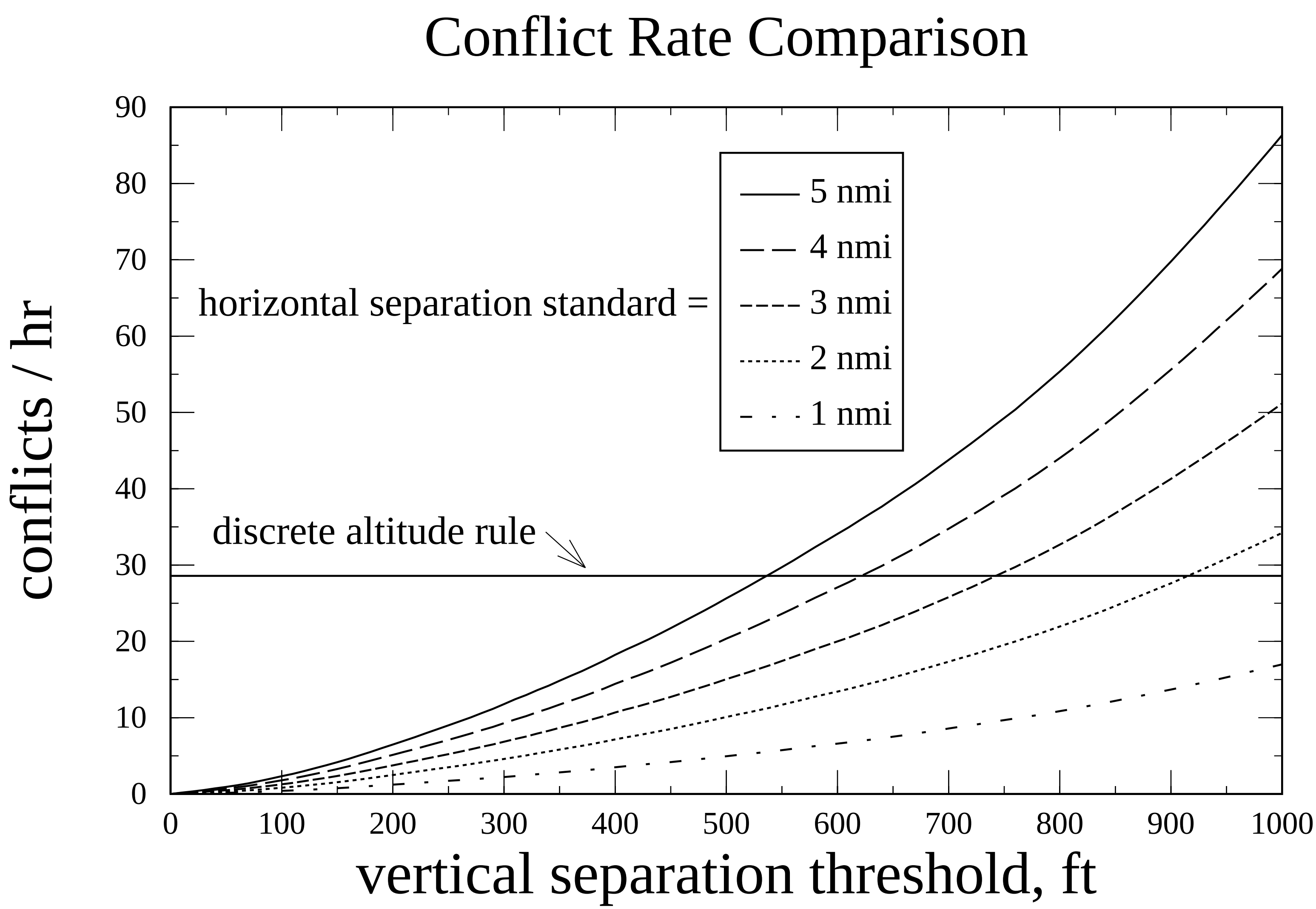
Vertical Resolution Opportunities

- Discrete altitude rule: few opportunities
  - requires minimum 1000 ft altitude change
  - puts aircraft in oncoming traffic
  - seldom used except in light traffic
- Linear altitude rule: many opportunities
  - large-angle conflicts: small altitude change
  - does not put aircraft in oncoming traffic
  - effective for large-angle conflicts


Vertical Resolution Opportunities
conflicts resolved, %
0
20
40
60
80
100
0
100
200
300
400
500
600
700
800
900
1000
vertical maneuver threshold, ft
linear altitude rule
discrete altitude rule

Advantages of Vertical Conflict Resolution

- more efficient than horizontal resolution
  - vertical separation requirement is less
  - altitude maneuvers largely conservative
  - efficiency less dependent on range
- much simpler than horizontal resolution
  - simple, robust scalar computations
  - much less sensitive to prediction error
  - accuracy independent of range
- Facilitates autonomous conflict resolution


Conflict Rate Comparison
90
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
800
900
1000
conflicts / hr
vertical separation threshold, ft
horizontal separation standard =
5 nmi
4 nmi
3 nmi
2 nmi
1 nmi
discrete altitude rule

Conflict Rate Factors

with discrete rule (5 nmi/1000 ft) as baseline

vertical threshold	horizontal separation standard			
	1 nmi	2 nmi	3 nmi	5 nmi
1000 ft	0.59	1.20	1.79	3.02
800 ft	0.38	0.77	1.14	1.94
500 ft	0.17	0.35	0.53	0.90

Conclusion: The Linear Altitude Rule

- Greatly reduces collision rates (without ATC)
- Greatly reduces collision closing speeds
- Increases conflict rate
- Increases vertical resolution opportunities
  - Simpler and more efficient resolution
  - Facilitates autonomous resolution
- May allow reduced horizontal separation
  - Improved resolution efficiency
  - Increased airspace capacity