A Real-time Turbulence Map for any National Airspace System (NAS) in the World

A passive system using GPS

Providing warning to all aircraft whose intended route takes them into harm's way

Produced by a unique and patented technology

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Let’s stop flying into turbulence to find it!

Let’s start avoiding turbulence!

Stop wine and coffee spills in our laps!

Stop bouncing flight attendants around the cabin

Atmospheric Turbulence is extremely complex!

No mathematical solution nor adequate model exists

Turbulence pulls energy from the mean flow at large scales -- this gain approximately balanced by viscous dissipation at very small scales – when it exists, it is continuous

Turbulence requires a continuous supply of energy (for such viscous losses). If no energy is supplied, turbulence decays rapidly – thus it can come and go rapidly

Turbulence impact on aviation is huge, will be larger in future

Turbulence causes $200 million in losses per year for US airlines

Impact greater in future with carbon taxes, and with NowGen & NextGen

Giovanni Bisignani (CEO of IATA) claims: “ shaving one minute off each commercial flight would save 5.0 tons of CO2 emissions and $3.8 billion in fuel costs each year ”

Better weather products through improved environmental sensors on aircraft are coming (more accurate temperature and water vapor sensors) which will help make such cost and emission savings possible

Turbulence will have major role in reducing the otherwise quite efficient NextGen operational procedures – examples of “’flow corridors” and “choreographed ascent / descent” are provided on next slides

Flow Corridors: long tubes or “bundles of near parallel 4DT assignments which achieve a very high traffic throughput

Corridors planned in advance; adjusted every 2 hours with accurate wx forecasts for efficiency – use of jet stream winds, avoiding turbulence, convection [temp (T) & water vapor [q])

Sudden corridor change [rapidly growth in enroute convection or moderate to severe turbulence, loss of key terminal] could lead to massive delays, safety issues, etc.

Unlike havoc on highway where autos can come to a stop
-- high density a/c traffic needs to be shuffled somewhere!

Choreographed Arrival/Departure (future plans)

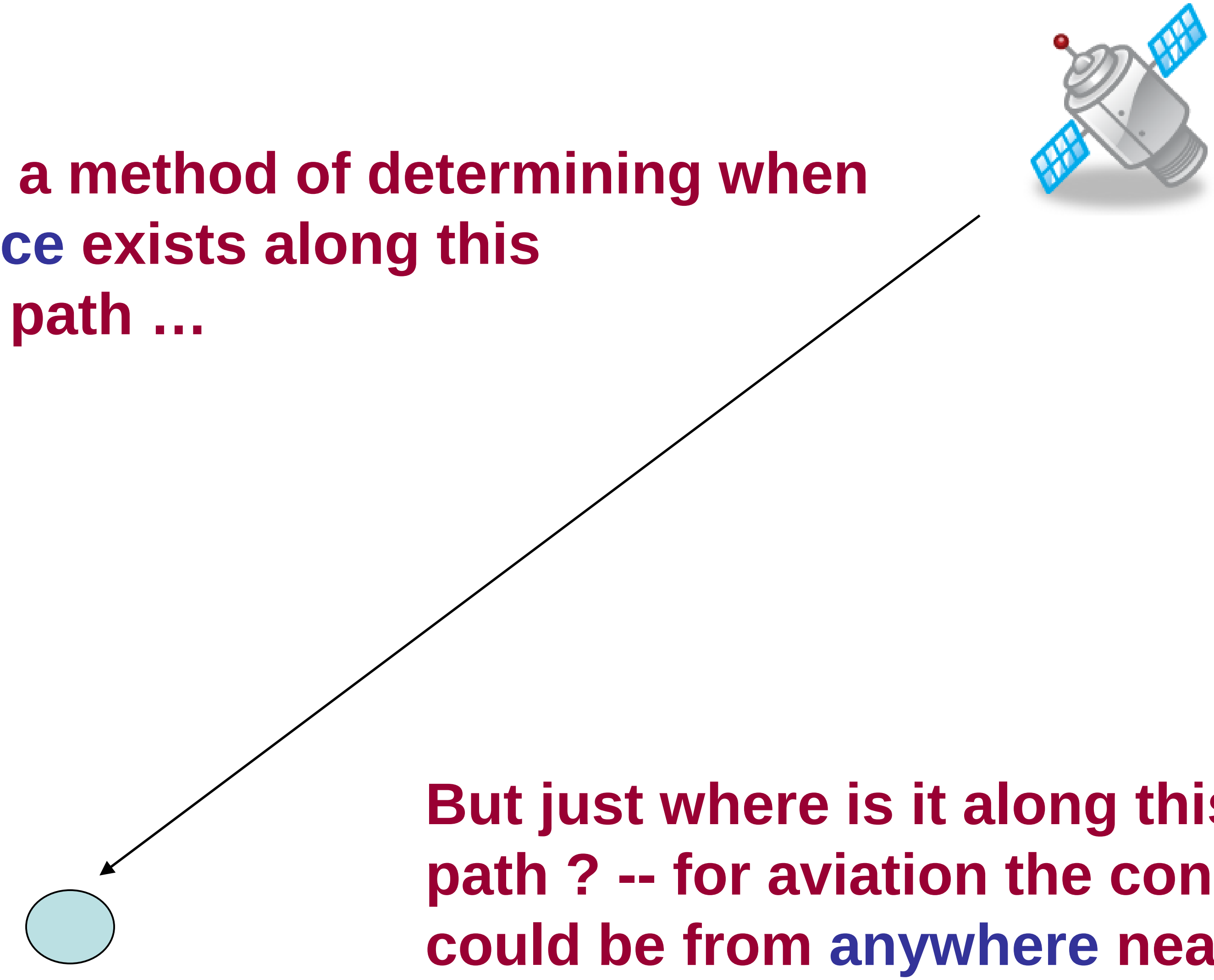
Airport terminals will have 4-D picture of terminal area (out to ~ 150 nm radius) from forecast model with 5 min refresh rate

Continuous descent approach (CDA) can occur in all weather conditions, with mixed fleets, and even at busy terminals!

However, need accurate wind, temp (T), and water vapor (q) from commercial aircraft in the greater (150 nm) terminal area for analysis and projection of convection: turbulence, thunderstorms, microbursts, and wake vortices

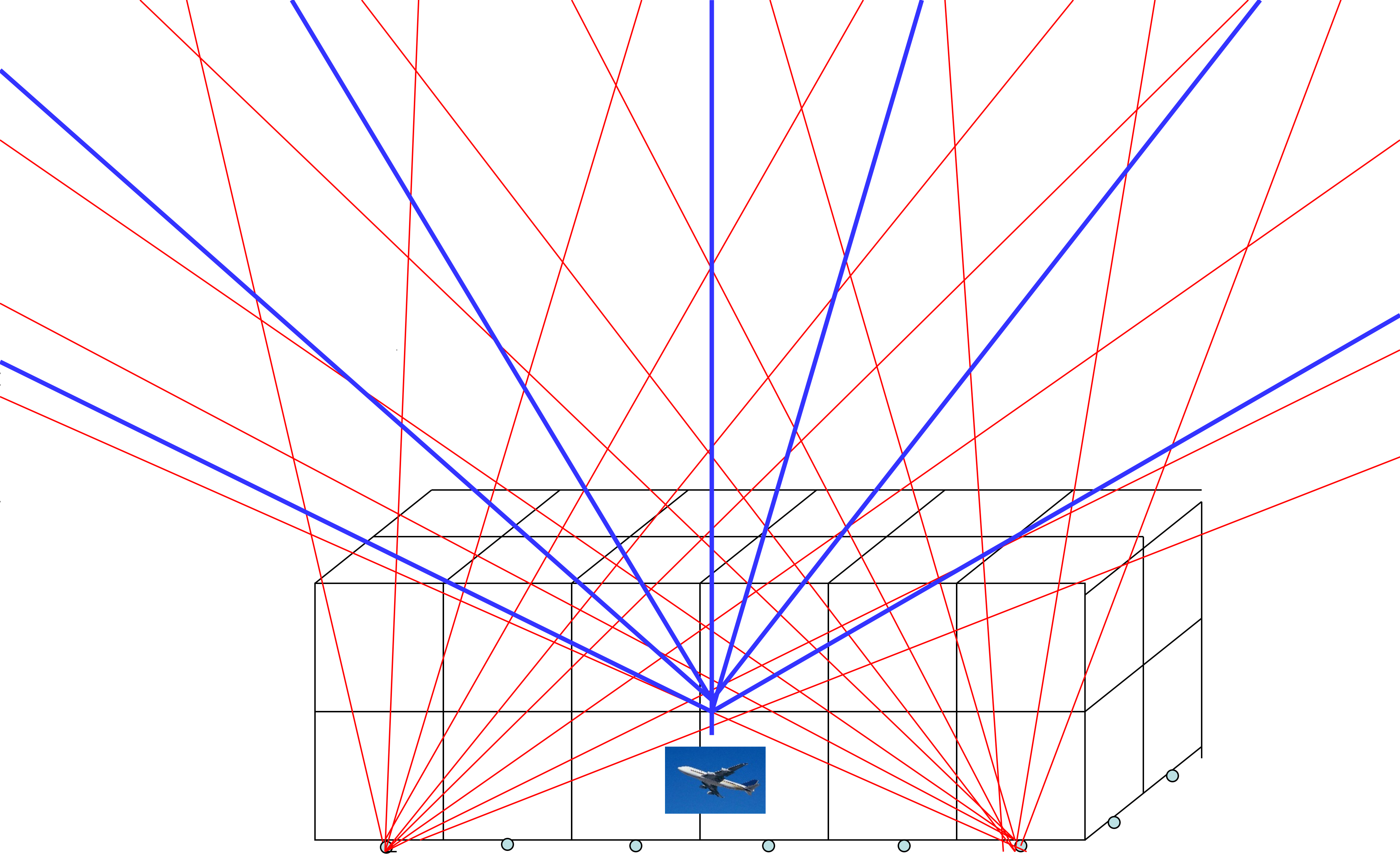
Pilot / controller exchange in terminal area will help, but the sudden onset or demise of turbulence will cause inefficient operations or worse in this dense traffic environment

We have a method of determining when turbulence exists along this GPS ray path …

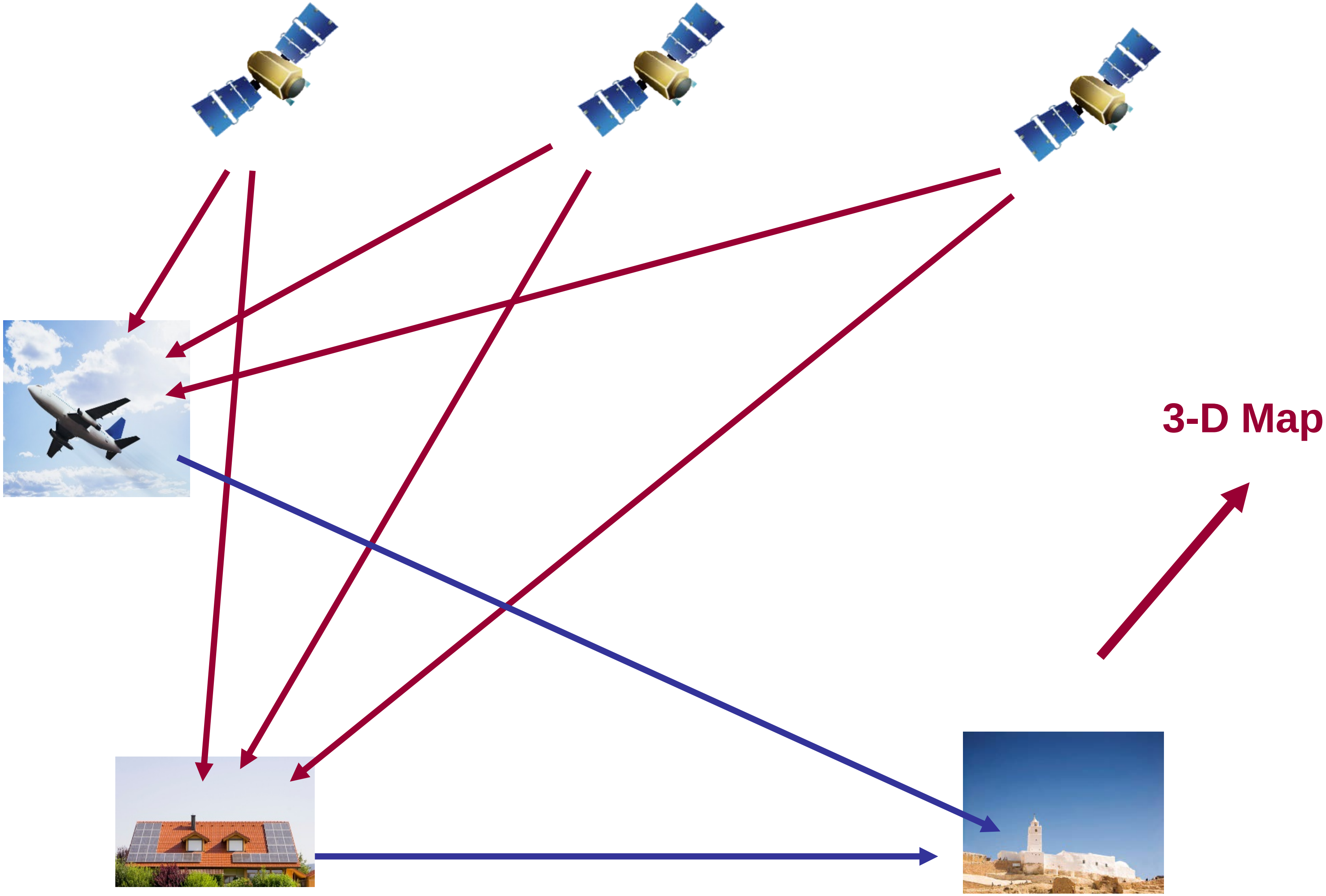


GPS receiver

But just where is it along this ray path ? -- for aviation the concern could be from anywhere near the surface to 40,000 feet



Solution: provide **more GPS rays** than **grid points** using both **airborne** and **ground-based** GPS receivers!!



3-D Map

GPS Surface Site

Turbulence Processing Center

Patent Claims Cover Several Aspects of Business Plan

GPS receivers on commercial aircraft and at ground sites

Communication of variance information from each receiver to the Turbulence Processing Center (TPC)

TPC computes geometry of GPS rays

TPC uses unique algorithms and special techniques to produce national or regional maps around the Earth

Communication of tailored products to Air Navigation Service Providers (ANSP), pilots, dispatch, and others with need to know

Summary of GPS errors removed

GPS signals travel at speed of light through a vacuum, but the rays are slowed (Δ time delay) by effects of temperature (T) & water vapor (q) These averaged delays need not be removed for the turbulence product

A variety of processes remove other errors: ionospheric delay, receiver clock errors, satellite clock errors and ephemeris errors (WAAS and LAAS)

The mean GPS signal delay is a function of the ~ laminar fluid flow -- the (nearly horizontally uniform) temperature (T) and water vapor (q) fields – the fluid properties which get colder and drier as one goes higher in the atmosphere

Why GPS variance reveals atmospheric turbulence

Mean GPS signals are typically slowly varying: given by an equation involving T and q. Scientists have assumed values of T and approximated q or vice versa. We do not need to separate effects of T and q in the turbulence calculation

Turbulence is a function of the fluid flow -- not the fluid itself which upsets the laminar flow conditions in T and q when the turbulence is present -- producing the high frequency variability (variance of the GPS signal delay about the mean)

The variance data about the geophysical mean signal (the atmosphere’s excess delay due to temperature (T) and water vapor (q)) will be computed by the GPS receiver.

Given 30 consecutive samples X (i) of excess delay from a single ray, the variance is:

Variance = $\{ \Sigma (X(i) - u)^2 \} / 30$ where $i = 1,30$

and where u is the mean of the sample coming from the T and q present in the fluid (atmosphere); the variance comes from the fluid flow (turbulence) disturbing the flow

Variance values for each GPS slant path will be processed by the GPS receiver software – then sent to the TPC

Variance of electromagnetic signals (or width of spectral return) has been used for turbulence identification before

Aircraft instruments (failed because warning not sufficient)

- radar
- infrared rays
- lasers

Ground detection

- Doppler lidar
- radar

GPS studies

- various studies
- see examples below

The passive GPS approach described here provides a near instantaneous view of turbulence in the entire national air space – if there are more GPS rays than grid points over the 3- dimensional space

National Turbulence Map from satellites in view (7 of 8 used)

Variance information computed in GPS receiver from 5 rays (each 6 seconds apart) simultaneously from 7 visible satellites and communicated as single packet of info every 30 seconds

Repeat above every 3 minutes (duty cycle 30 s / 3 m = 1 / 6) so TPC computes national sub-map every 3 minutes

Produce **national map** and products (based upon 3 sub-maps) every 15 min; disseminate map and product

Turbulence map produced from solving large over-determined matrix equation A X = B
(considerable discussion on this later)

System Design Concepts

Need more GPS rays than grid points

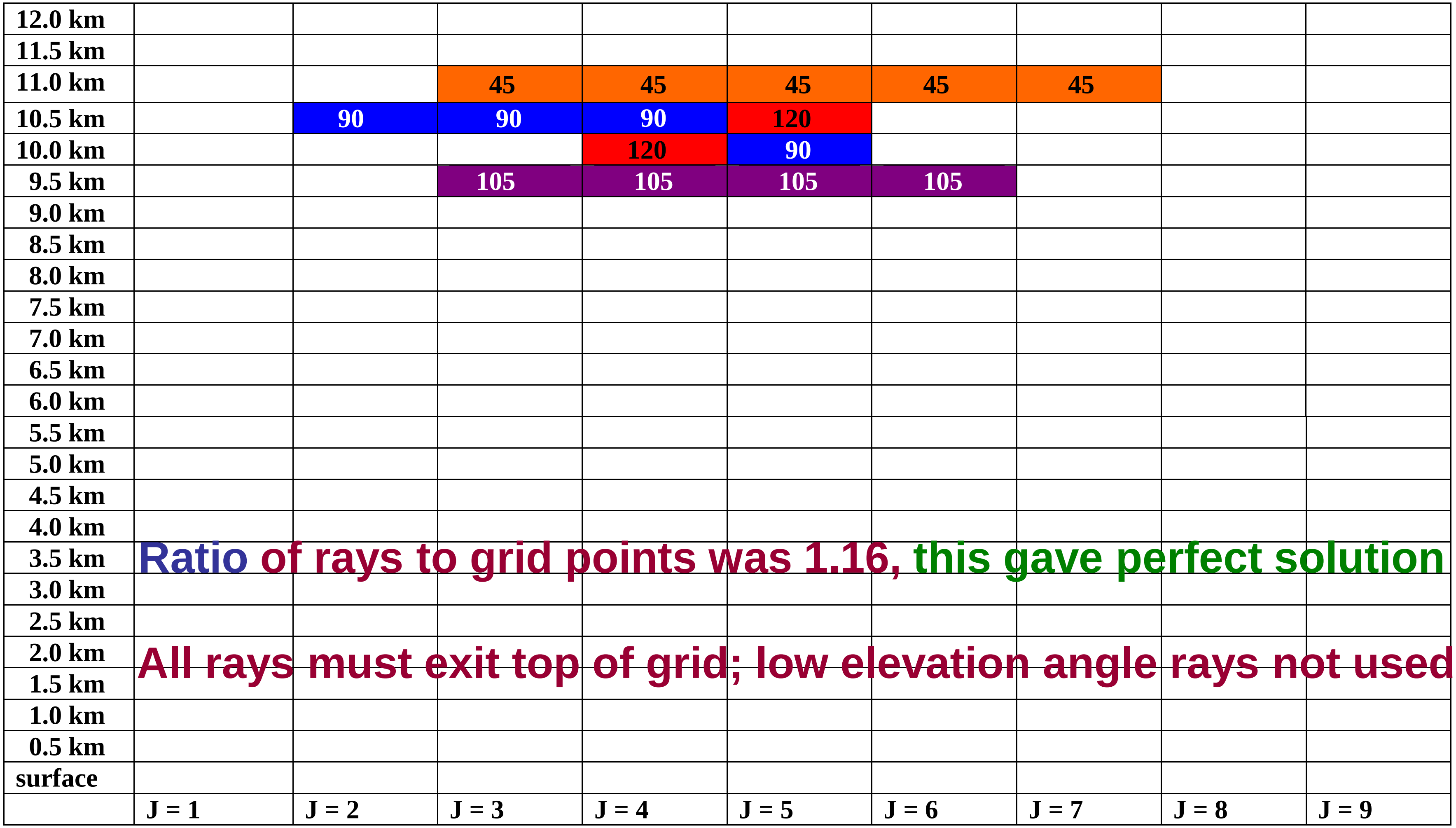
Useful national map would have approximately 250,000 grid points (extending over ocean & into Canada and Mexico up to 40,000 feet)

Best results with ratio of (# of rays) / (# of points) = 1.2

Typical sequence of 7500 surface sites and 1000 active aircraft yields ~ 300,000 rays – providing a Ratio ~ 1.2

3.5 years of extensive simulations performed

Turbulence over 4 vertical layers with 4 intensities (LGT, MOD, SVR, & mixed)



12.0 km									
11.5 km									
11.0 km			**45**	**45**	**45**	**45**	**45**		
10.5 km		**90**	**90**	**90**	**120**				
10.0 km				**120**	**90**				
9.5 km			**105**	**105**	**105**	**105**			
9.0 km									
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1.0 km									
0.5 km									
surface									
	J = 1	**J = 2**	**J = 3**	**J = 4**	**J = 5**	**J = 6**	**J = 7**	**J = 8**	**J = 9**

Ratio of rays to grid points was 1.16, this gave perfect solution

All rays must exit top of grid; low elevation angle rays not used

Can test over an abbreviated horizontal grid in 2-D with full vertical scale like 225 grid points shown here, or achieve same results with extended grid (2525 grid points and 3720 rays performed on laptop pc)

Many simulations performed – always more rays than grid pts

Turbulence patterns (simple to complex) reproduced using various 2 and 3-D grid resolutions; satellites and aircraft moved; and random errors added to ray values to find possible failure modes – none found!

Various mathematical nuances have been employed to handle

- the geometric sensitivity of the A matrix
- small random errors from several sources
- anisotropic conditions for large scale turbulence

All are discussed later (for reference, one is mentioned now)

The scaled variance values (0, 2, 3, and 4) for (no, light, moderate, and severe turbulence) communicated from the GPS receivers are rescaled to (0, 60, 90, and 120) in the TPC

Expected Revenue

Facts from 2007 Air Transport Association (ATA) Annual Report

-- 11,365,000 aircraft departures from US airlines

-- 769.2 M passengers per this year

-- charge $15 per aircraft departure for total turbulence (24 by 7) coverage this is $ 170.5 M per year

-- charge $0.22 per passenger for same total coverage this is $ 169.2 M per year

Revenue funds paid by Federal Government Agency and/or by air carriers with cost added to ticket price

Expenses: Capital costs and recurring costs

Capital costs

1000 aircraft equipped	cost = $10 K each	= $ 10.0 M
7500 GPS surface sites	cost = $1.4 K each	= $ 10.5 M
Initial installation costs	$10 M (a/c) $10 M (sfc)	= $ 20.0 M

Recurring costs

Aircraft (1000) communication costs	$ 4.3 M / year
Ground communication (7500) costs	$ 4.5 M / year
TPC personnel costs (salary & benefits)	$ 6.0 M / year
Computer, facilities, overhead, travel, etc.	$ 6.0 M / year
Receiver maintenance and replacement (after first 2 years) at 5% of capital costs	$ 1.1 M / year
TOTAL	**$ 21.9 M / year**

Return on Investment (ROI)

Profit per year = ($170.5 M - $21.9 M) = $ 148.6 M per year

Full accounting with depreciation of assets, etc., later but assume effective tax rate of 15% gives PAT = $126.3 M

Knowledge of where turbulence exits in advance reduces personnel anxiety, saves fuel use, reduces CO_2 emissions, and will be essential in safe, optimal use of new operations in NowGen and NextGen

ROI achieved one year after full operation; opportunity for profitable investment with long term cash cow; help make the world a better place to fly!

Section II – Greater detail follows (# 23 - # 40)

Facts on Turbulence

Matrix detail

Singular Value Decomposition

Turbulence issues / tests

Sub-maps: why and options

Atmospheric Turbulence is extremely complex!

Turbulent flows are always dissipative; viscous shear stresses perform deformation work that increase the internal energy of the fluid at the expense of kinetic energy of the turbulence.

Requires a continuous supply of energy (for viscous losses), if no energy is supplied, turbulence decays rapidly!

Turbulence can come and go rapidly; and convert from light to severe and back again rapidly

No mathematical solution nor adequate model exists

It is not a feature of fluids, but is a result of fluid flows!

Why GPS variance reveals atmospheric turbulence

The mean GPS signal delay is a function of the fluid itself : the laminar (nearly horizontally uniform) temperature (T) and water vapor (q) fields – which get colder and drier as one goes higher in the atmosphere

The signal is nearly constant: given by an equation involving T and q. Some scientists assume T and estimate q or vice versa, but we need not separate the two

Turbulence is a function of the fluid flow -- which upsets the laminar conditions in T and q -- when the turbulence is present -- producing the high frequency variability (variance of the GPS signal delay)

Most rays will not see any turbulence – not that ubiquitous

Identifying small thin layers of turbulence is relatively easy (turbulence is homogeneous and isotopic on small scales)

Moderate to severe turbulence on large scale is less likely to be isotropic (same variability in all directions), but perhaps nearly so from a GPS variance perspective (we will check on this impact in calculations shown below)

The blending of nearly equal but disparate information is aided by the scaling process of assigning measured variance values into the broad categories of light (2) moderate (3) and severe (4) – this based upon previous calibration

The re-scaling of variance values to (60, 90, and 120) performed at the TPC helps separate the various categories of turbulence (light, moderate, and severe) and aids this blending of information

The evaluation over and between sub-maps will also identify this blending – the important point is that such turbulent areas will be easily identifiable – if not precisely quantifiable within a category

Finally, additional quality control information from national radar data and automated and manual pilot reports completes the processing procedure

Variance of electromagnetic signals (or width of spectral return) has been used for turbulence identification before

Aircraft instruments (failed because warning not sufficient)

- radar
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- lasers

Ground detection

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The passive GPS approach described here provides a near instantaneous view of turbulence in the entire national air space – if there are more GPS rays than grid points over the 3- dimensional space

(Kleijer, et al) look at the GPS signal variance from a single ground site. Variance is attributed to turbulence in water vapor in the PBL. Values from 10 to 120 mm^2 are seen – suggesting we can differentiate intensity

(Kornman and Frehlich) look at single GPS occultations in upper atmosphere. Variance attributed to “temperature turbulence” related to velocity turbulence. The analyzed signals are consistent with “models” with estimated length scale of 3km.

The mechanical turbulence at these altitudes varies from a few meters to a few km. Convective turbulence (which is deeper) involves the instability (temperature and water vapor) of the atmosphere.

Our method will detect both types of turbulence simultaneously over the 3-D air space -- with more GPS rays than grid points

Mathematical method: Singular Value Decomposition (SVD)

Problem is solving $A X = B$ [using SVD]

A is a calculated matrix of (# of rays, # of grid points) (R x N)

X is solved for vector of turb. values X (# of points) (N x 1)

B is the measured vector of variances (# of rays) (R x 1)

$R > N$ $R / N > 1.2$ adds flexibility in system

The values change for each map: the grid is stationary, but the rays change as the GPS satellites and aircraft move -- changing the A’s and the B’s

Ray (in red) must exit top of grid

Location of GPS Receiver at site XSFC (Aircraft geometry similar)

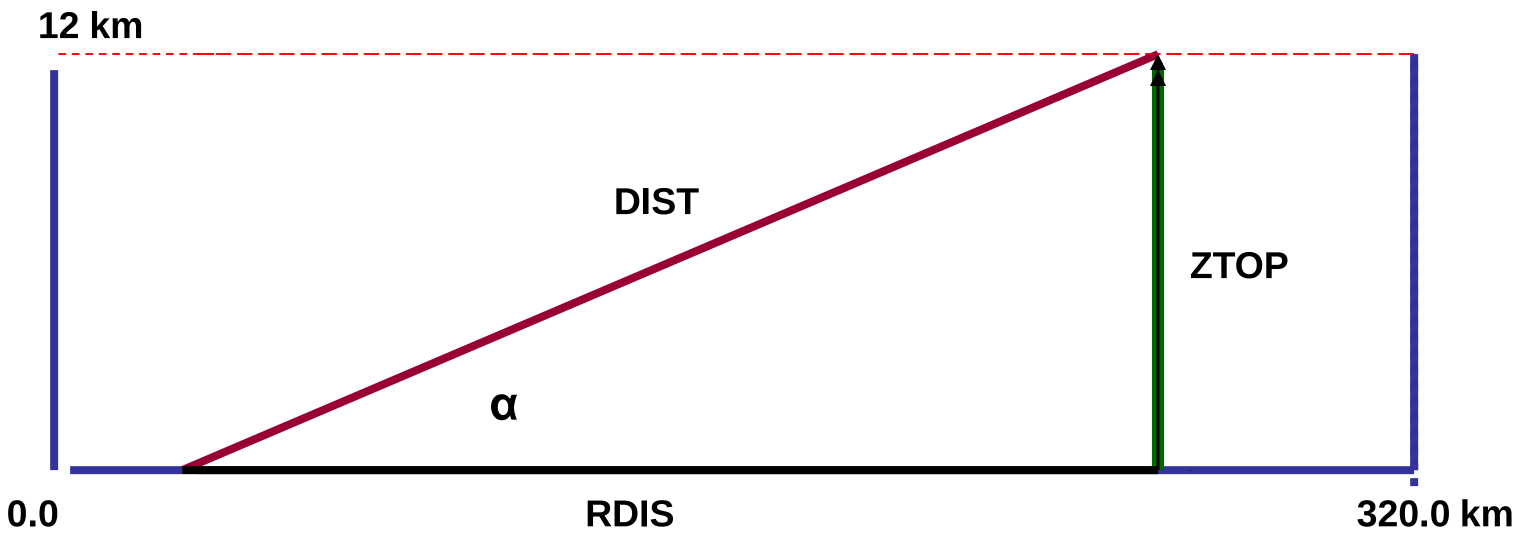
Tan (α) = ZTOP/RDIS; RDIS=ZTOP/Tan (α)   XLOC = XSFC +RDIS

IF (XLOC .LE. 0.0 .OR. XLOC .GE. 320.) NOT In grid

Number of points along ray (NSTEPS): Sin (α) = ZTOP / DIST

DIST = ZTOP / Sin (α)

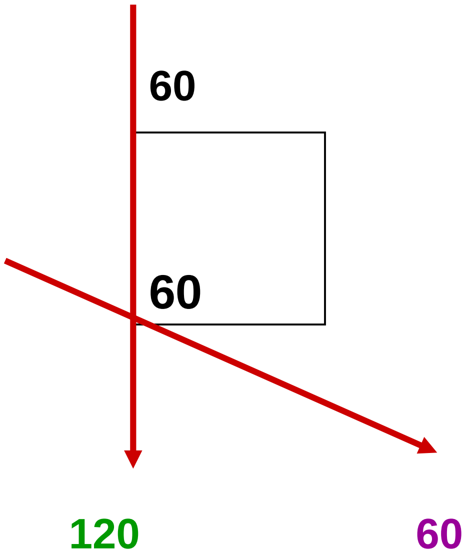
NSTEPS = DIST / ΔS = DIST / 0.5 km

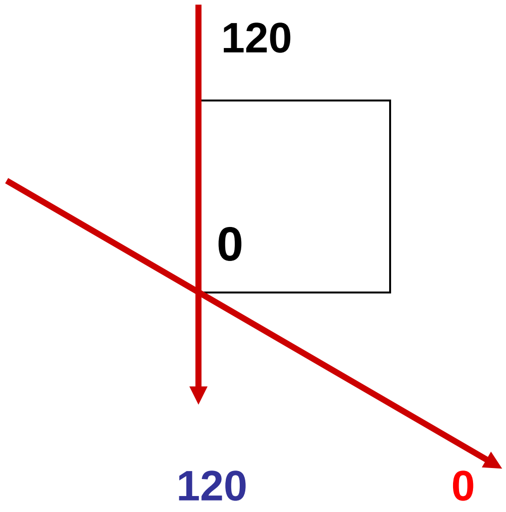


Cartoon not to scale: X distance over 26 times Z distance

How does method differentiate a vertical ray that sees a variance value of 120 (which could indicate 1 layer of severe turbulence or 2 layers of light (60) turbulence?

A single ray will not be able to do this, but two rays passing through a grid box can do so! Consider a graphic example (math example later)





Vertical ray 120 (above) could indicate vertical values on left or on the right, but the diagonal ray coming in as 60 or 0 gives the answer

Using power of Singular Value Decomposition (SVD)

Very powerful concept for dealing with matrices that are singular or are very close to singular.

Our problem is one where the A matrix is quite sparse (recall that it is an R x N matrix where R is the number of rays and N is the number of grid points) – a singe ray influences less than 1% of the grid points.

Singularities can occur in one of three ways:

While the geometry of the satellites and the GPS receivers affect the A matrix (it works extremely well with perfect data), it is possible that small changes in atmospheric conditions over the 30 s data gathering period could induce errors

Small random errors can occur for a variety of reasons which can manifest themselves as large errors with a such a matrix

Larger systematic errors can occur in large scale moderate or severe turbulence when the turbulence is anisotropic (intensity a function of direction)

Solving A X = b

$$\left(\quad A \quad \right)\left(X \right) = \left(b \right)$$

Using SVD

one has:

$$\left(\quad A \quad \right) = \left(\quad U \quad \right)\left(\mathrm{diag}\ W_j \right)\left(\quad V^T \quad \right)$$

$$\left(X \right) = \left(\quad V \quad \right)\left(\mathrm{diag}\ (1/W_j) \right)\left(\quad U^T \quad \right)\left(b \right)$$

Setting some of the smallest singular values [W(i)] = 0.0 solves these problems by producing a solution to A X = b, which while not exact, is best in the least square sense

Find Max W(i); set Thresh = (Max) x (Tol); if [W(i) < Thresh] then W(i) = 0.0

where Tol = tolerance chosen for problem at hand

We find for this GPS turbulence problem that:

Random errors require less W (i) be set to zero

Simple 2D model with N = 225: 22 of 225 W (i) = 0.0 or 9.8%

Larger 3D model with N = 2525: 250 of 2525 W(I) = 0.0 or 9.9%

Systematic (anisotropic) errors require more W (i) be set to zero

Simple 2D model with N = 225: 28 of 225 W (i) = 0.0 or 12.4%

Larger 3D model with N = 2525: 384 of 2525 W (i) = 0.0 or 15.2%

With random errors added to all the B –vector variance values (both turbulent and non-turbulent) the turbulent cells are still accurate to 95-99%, but the non-turbulent cells have errors ranging from extremely small (10^{-4}) to quite large

Via the A matrix, the SVD method disperses the largest errors to grid points with the least ray influence – thus points near the surface and grid edge get the largest errors. However, when setting the smallest W (i) values to zero, these singular value induced errors are reduced to below 60

TPC quality control (QC) procedures set all computed values less than the light turbulence value (60) to zero!

Other QC procedures: using pilot reports and automatic turbulence reports from aircraft for feedback; inter comparison and integration of significant radar echoes; etc.

Most rays will not see any turbulence – not that ubiquitous

Identifying small thin layers of turbulence is relatively easy (turbulence is homogeneous and isotopic on small scales)

Moderate to severe turbulence on large scale is less likely to be isotropic (same variability in all directions), but perhaps nearly so from a GPS variance perspective

The re-scaling of variance values to (60, 90, and 120) in the TPC for turbulence of (light, moderate, and severe) will help identify a blending of information when the conversion of the smallest W(i) values are set to zero

The important thing is that such blended turbulence areas are easily identifiable – if not precisely quantifiable

Simple 2-D model (J, K) with 8 surface stations and 5 a/c

Random Error Test: Single cell (5, 20) SDE = 0.1 on rays with B > 0.0

2D model with 225 points and 425 rays. **True value = 90.0**

TOL (10^{-4})	0.1	0.2	0.4	1.0	2.0	2.5	3.6	4.0
# of W(i) = 0	0	1	5	11	22	26	32	34
Max Error	6.34	6.24	4.58	3.43	2.26	2.50	2.93	3.05
Avg. value of turb. In feature	90.88	90.88	90.89	90.51	90.10	90.12	89.34	88.79

Note: SDE = 0.0 gives max error of 0.26 D -10

Begin with simple 2-D model with 8 surface stations and 5 a/c

Random Error Test: Single cell (5, 20) SDE = 1.0 on rays with B > 0.0

2D model with 225 points and 425 rays. True value = 90.0

TOL (10^{-4})	0.05	0.1	0.5	1.0	2.0	4.0	6.1	8.0
# of W(i) = 0	0	1	5	11	22	34	49	59
Max Error	63.50	62.25	44.85	35.10	18.79	12.72	7.51	11.68
Avg. value of turb. In feature	99.82	98.81	98.97	98.27	99.76	96.57	89.81	84.07

Error reduced by a factor of 63.50 / 7.51 = 8.46 Note T = 89.81 vs 90.0

Begin with simple 2-D model with 8 surface stations and 5 a/c

Random Error Test: Single cell (5, 20) SDE = 1.0 on all rays, but ray value plus random error always > 0.0 [QC allows no ray with value < 0.0]

2D model with 225 points and 425 rays. True value = 90.0

TOL (10^{-4})	0.05	0.1	0.5	1.0	2.0	4.1	7.0	8.0
# of W(i) = 0	0	1	5	11	22	36	53	59
Max Error	329.5	123.1	100.5	49.06	24.71	10.01	18.90	20.58
Avg. value of turb. In feature	97.74	98.05	97.33	97.76	99.23	85.89	85.30	83.76

Error reduced by a factor of 329.5 / 10.01 = 32.9

Begin with simple 2-D model with 8 surface stations and 5 a/c

Random Error Test: Single cell (5, 20) SDE = 2.0 on all rays, but ray value plus random error always > 0.0 [QC allows no ray with value < 0.0]

2D model with 225 points and 425 rays. True value = 90.0

TOL (10^{-4})	0.05	0.1	0.5	1.0	4.1	7.0	8.0	10.0
# of W(i) = 0	0	1	5	11	36	53	59	67
Max Error	659.1	246.1	201.2	99.51	19.87	17.77	15.01	28.58
Avg. value of turb. In feature	106.6	107.3	107.6	109.7	107.3	93.04	91.25	76.84

Error reduced by a factor of 659.1 / 15.01 = 43.9