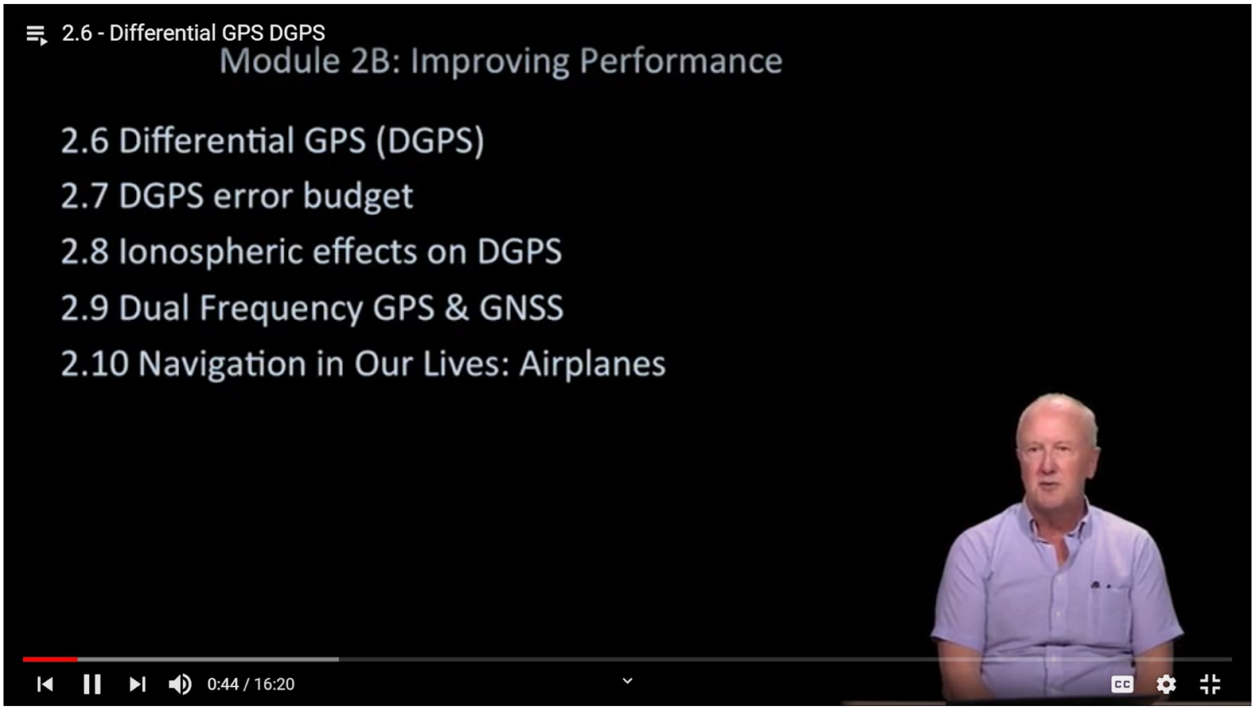
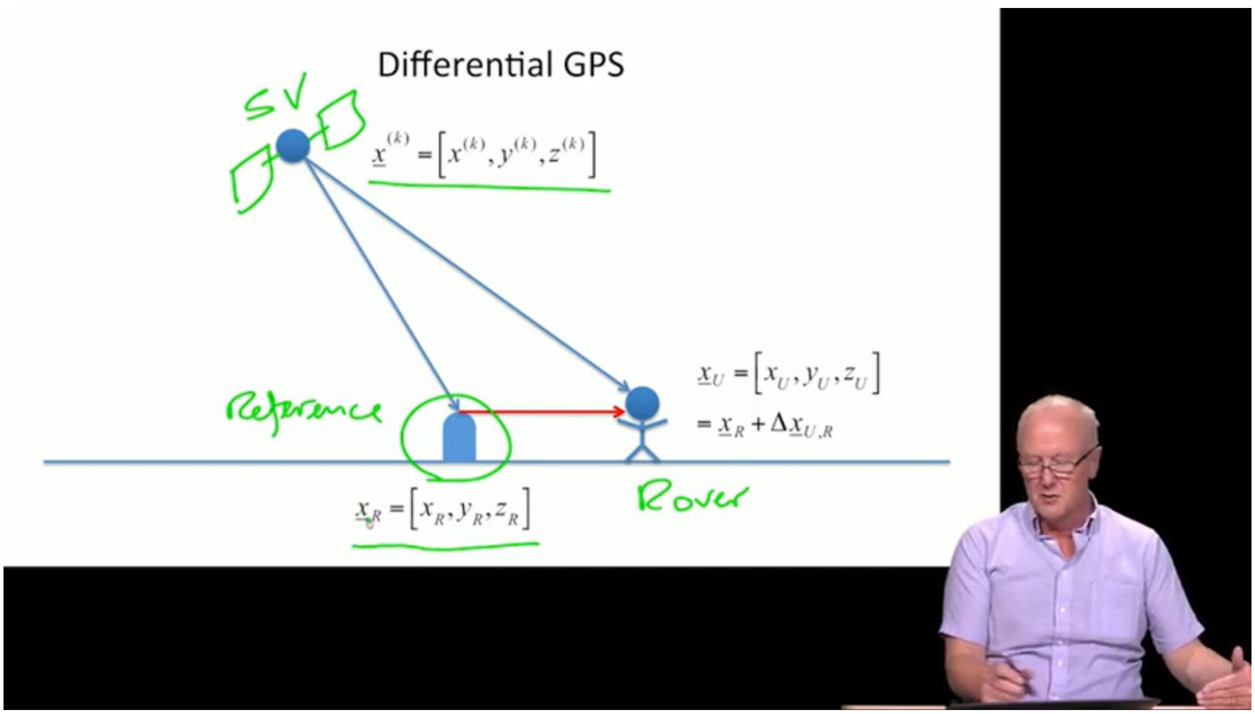

2.6 - Differential GPS DGPS
Module 2B: Improving Performance
2.6 Differential GPS (DGPS)
2.7 DGPS error budget
2.8 Ionospheric effects on DGPS
2.9 Dual Frequency GPS & GNSS
2.10 Navigation in Our Lives: Airplanes
0:44 / 16:20


Differential GPS
SV
$\underline{x}^{(k)} = [x^{(k)}, y^{(k)}, z^{(k)}]$
$\underline{x}_U = [x_U, y_U, z_U]$
$= \underline{x}_R + \Delta\underline{x}_{U,R}$
Reference
Rover
$\underline{x}_R = [x_R, y_R, z_R]$

$$\tau_U = \left|\underline{x}^{(k)} - \underline{x}_U\right| + I + T + b_U - B^{(k)} + \nu$$

$$\tau_0 = \left|\underline{x}^{(k,B)} - \underline{x}_{U,0}\right| + \hat{I} + \hat{T} + b_{U,0} - B^{(k,B)}$$

$$\delta\tau = -\Delta\underline{x}_{U,R} \bullet \underline{1}_U^{(k)} + \delta\underline{x}^{(k)} \bullet \underline{1}_U^{(k)} + \delta b_U - \delta B^{(k)} + \delta I + \delta T + \nu$$

$$\tau_U = \left|\underline{x}^{(k)} - \underline{x}_U\right| + I_U + T_U + b_U - B^{(k)} + \nu_U$$

$$\tau_R = \left|\underline{x}^{(k)} - \underline{x}_R\right| + I_R + T_R + b_R - B^{(k)} + \nu_R$$

$$\tau_U - \tau_R = \left|\underline{x}^{(k)} - \underline{x}_U\right| - \left|\underline{x}^{(k)} - \underline{x}_R\right| + \Delta I + \Delta T + b_U - b_R + \nu_U - \nu_R$$

$$\tau_U = \left|\underline{x}^{(k)} - \underline{x}_U\right| + I + T + b_U - B^{(k)} + \nu$$

$$\tau_0 = \left|\underline{x}^{(k,B)} - \underline{x}_{U,0}\right| + \hat{I} + \hat{T} + b_{U,0} - B^{(k,B)}$$

$$\delta\tau = -\Delta\underline{x}_{U,R} \bullet \underline{1}_U^{(k)} + \delta\underline{x}^{(k)} \bullet \underline{1}_U^{(k)} + \delta b_U - \delta B^{(k)} + \delta I + \delta T + \nu$$

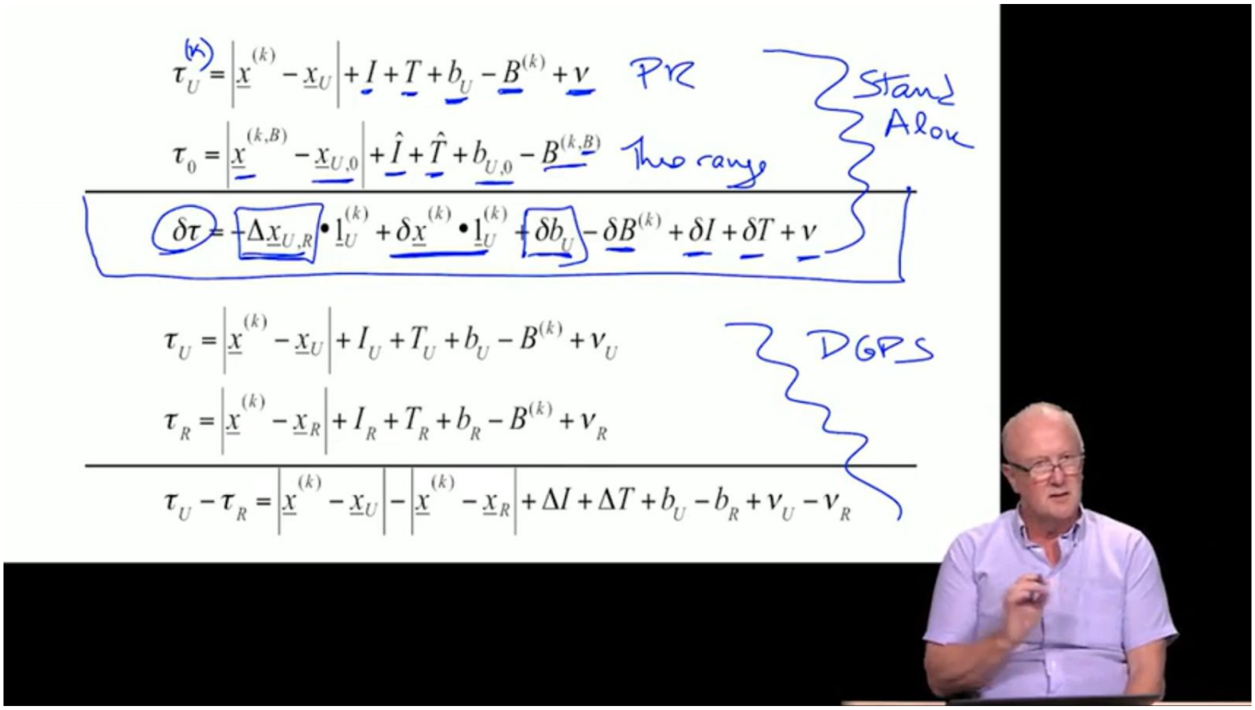
Stand Alon

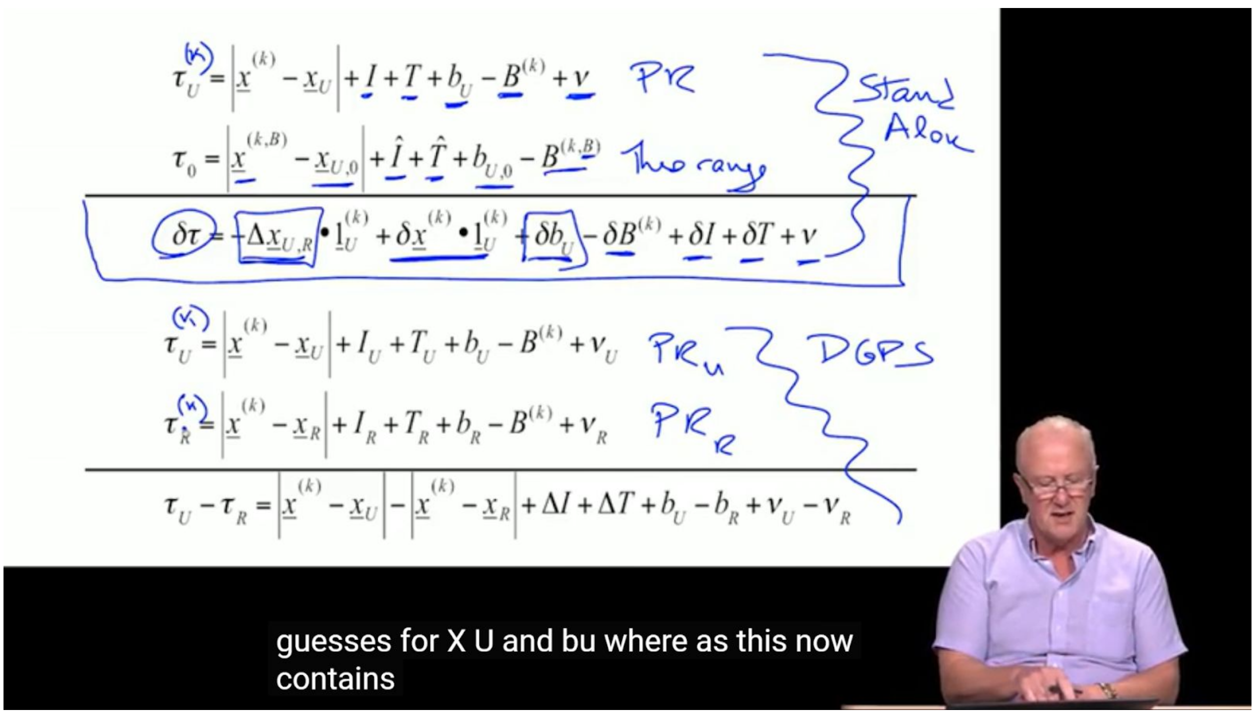
$$\tau_U = \left|\underline{x}^{(k)} - \underline{x}_U\right| + I_U + T_U + b_U - B^{(k)} + \nu_U$$

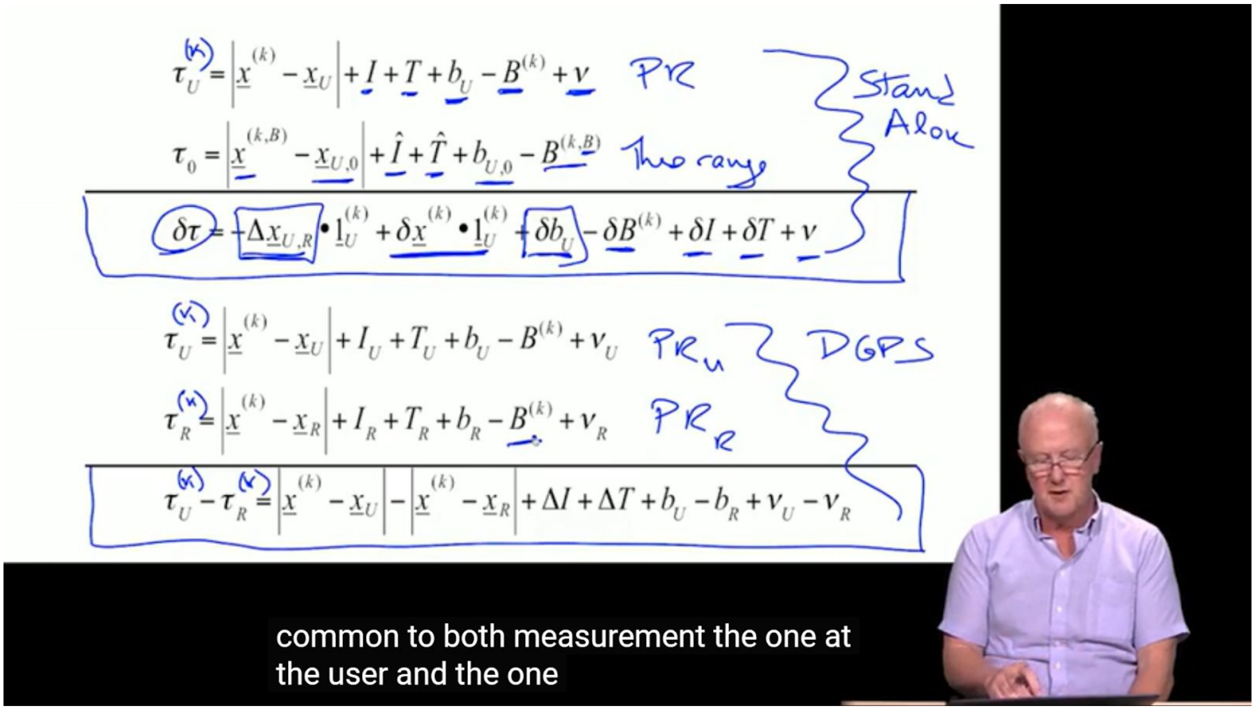
$$\tau_R = \left|\underline{x}^{(k)} - \underline{x}_R\right| + I_R + T_R + b_R - B^{(k)} + \nu_R$$

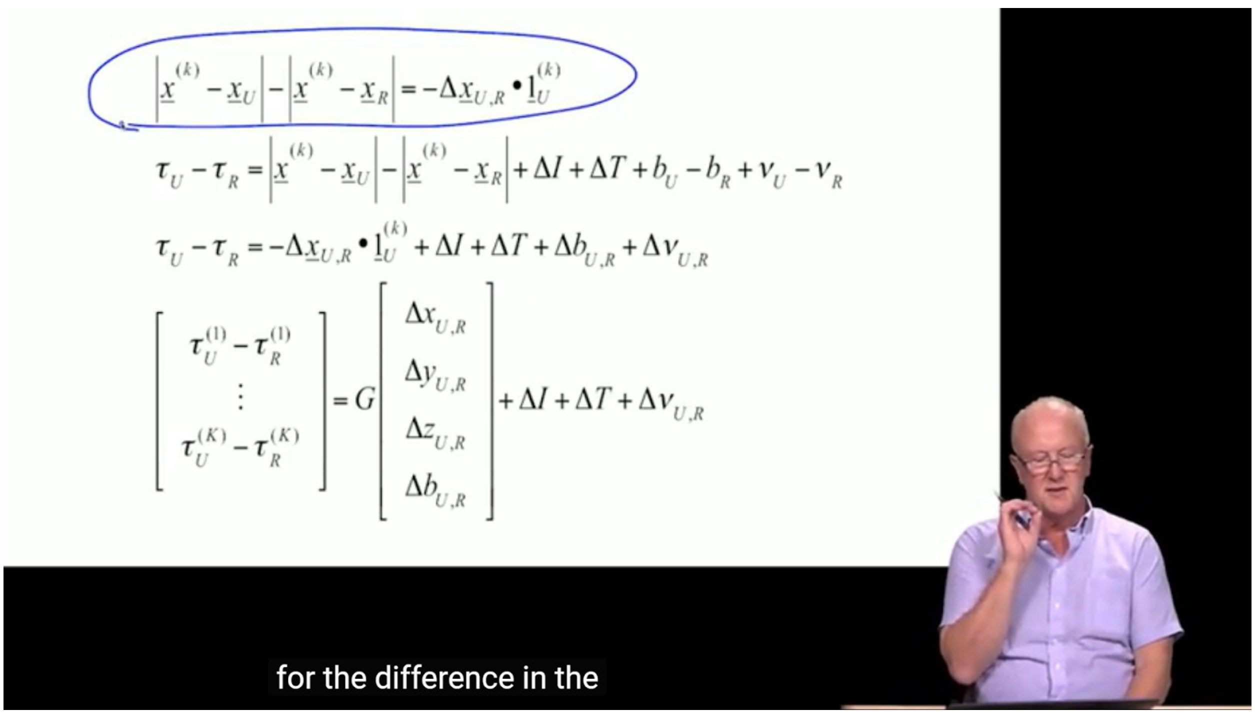
$$\tau_U - \tau_R = \left|\underline{x}^{(k)} - \underline{x}_U\right| - \left|\underline{x}^{(k)} - \underline{x}_R\right| + \Delta I + \Delta T + b_U - b_R + \nu_U - \nu_R$$

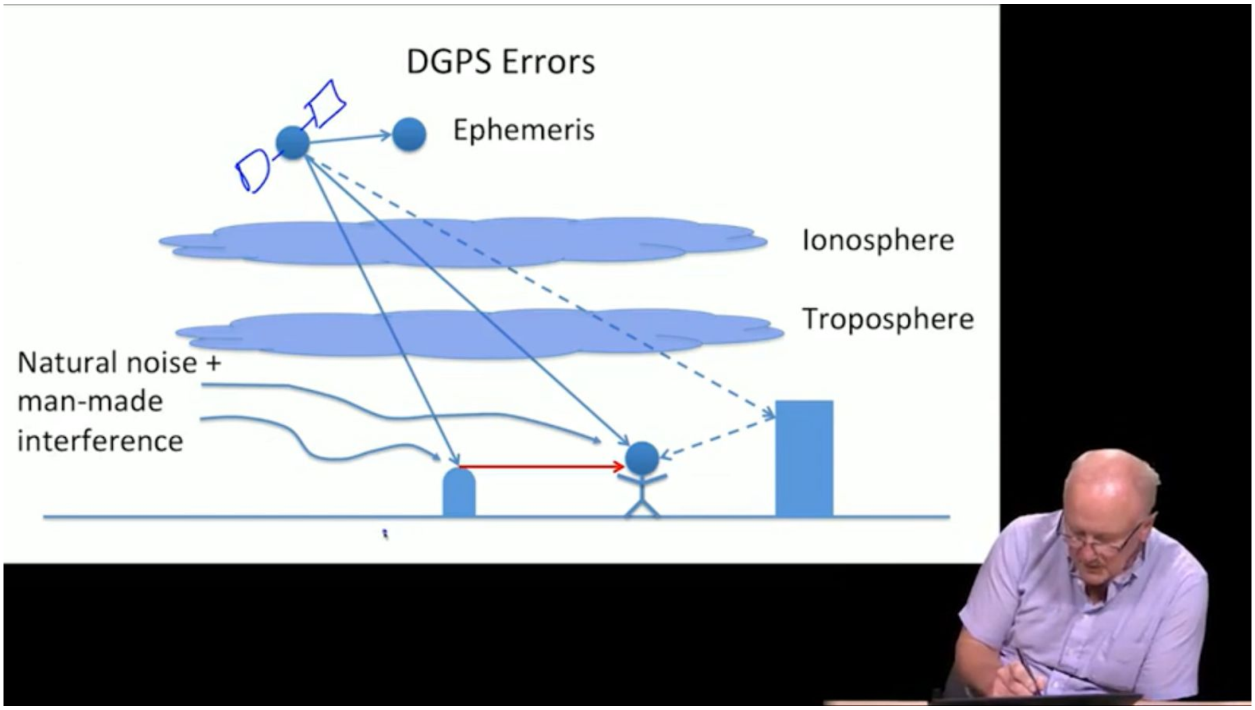
DGPS

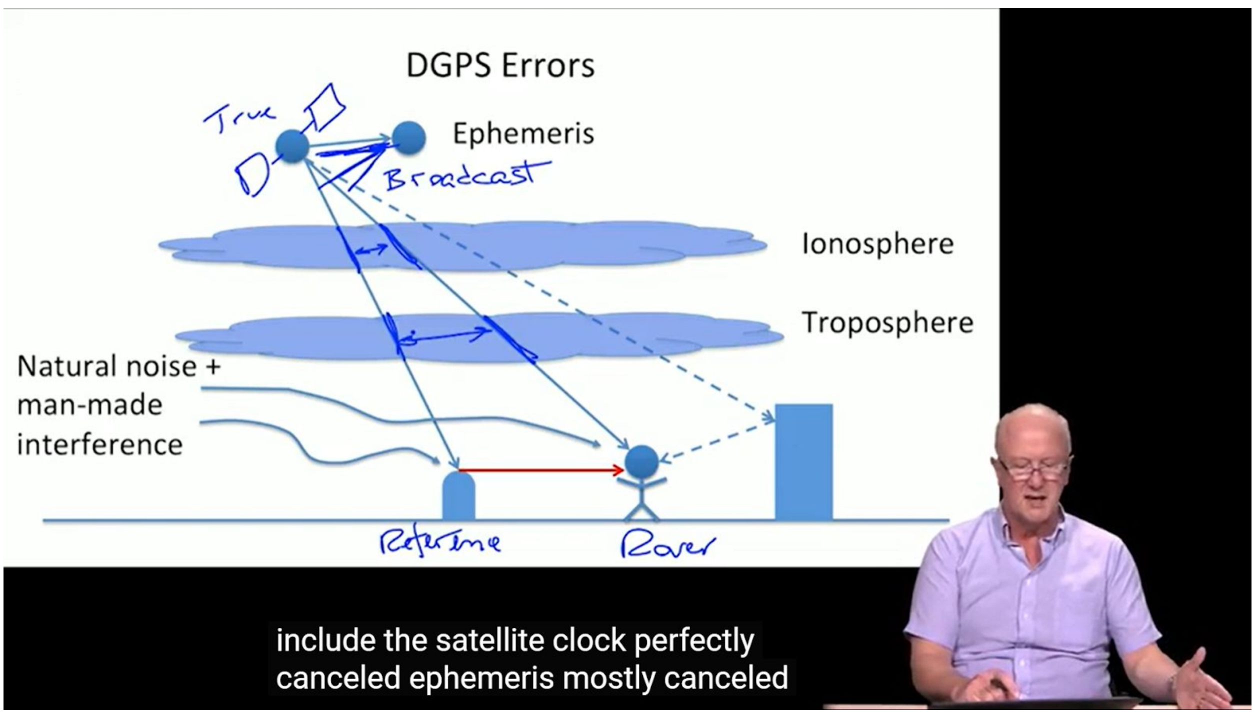

$\tau_U^{(k)} = \left|\underline{x}^{(k)} - \underline{x}_U\right| + I + T + b_U - B^{(k)} + \nu$
PR
$\tau_0 = \left|\underline{x}^{(k,B)} - \underline{x}_{U,0}\right| + \hat{I} + \hat{T} + b_{U,0} - B^{(k,B)}$
Theo range
$\delta\tau = -\boxed{\Delta \underline{x}_{U,R}} \bullet \underline{1}_U^{(k)} + \delta \underline{x}^{(k)} \bullet \underline{1}_U^{(k)} + \boxed{\delta b_U} - \delta B^{(k)} + \delta I + \delta T + \nu$
Stand Alon
$\tau_U = \left|\underline{x}^{(k)} - \underline{x}_U\right| + I_U + T_U + b_U - B^{(k)} + \nu_U$
$\tau_R = \left|\underline{x}^{(k)} - \underline{x}_R\right| + I_R + T_R + b_R - B^{(k)} + \nu_R$
$\tau_U - \tau_R = \left|\underline{x}^{(k)} - \underline{x}_U\right| - \left|\underline{x}^{(k)} - \underline{x}_R\right| + \Delta I + \Delta T + b_U - b_R + \nu_U - \nu_R$
DGPS

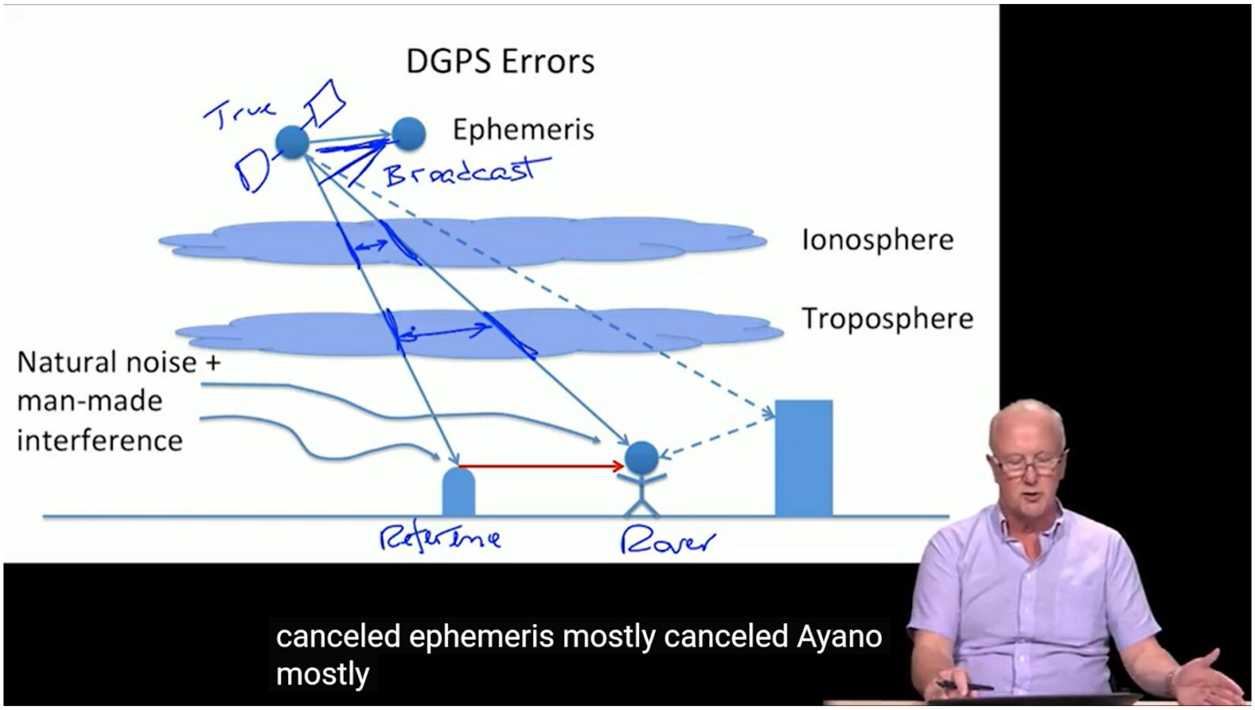

$\tau_U^{(k)} = \left|\underline{x}^{(k)} - \underline{x}_U\right| + I + T + b_U - B^{(k)} + \nu$
PR
$\tau_0 = \left|\underline{x}^{(k,B)} - \underline{x}_{U,0}\right| + \hat{I} + \hat{T} + b_{U,0} - B^{(k,B)}$
Theo range
$\delta\tau = -\boxed{\Delta \underline{x}_{U,R}} \bullet \underline{1}_U^{(k)} + \delta \underline{x}^{(k)} \bullet \underline{1}_U^{(k)} + \boxed{\delta b_U} - \delta B^{(k)} + \delta I + \delta T + \nu$
Stand Alon
$\tau_U^{(k)} = \left|\underline{x}^{(k)} - \underline{x}_U\right| + I_U + T_U + b_U - B^{(k)} + \nu_U$
PR_U
$\tau_R^{(k)} = \left|\underline{x}^{(k)} - \underline{x}_R\right| + I_R + T_R + b_R - B^{(k)} + \nu_R$
PR_R
$\tau_U - \tau_R = \left|\underline{x}^{(k)} - \underline{x}_U\right| - \left|\underline{x}^{(k)} - \underline{x}_R\right| + \Delta I + \Delta T + b_U - b_R + \nu_U - \nu_R$
DGPS
guesses for X U and bu where as this now
contains

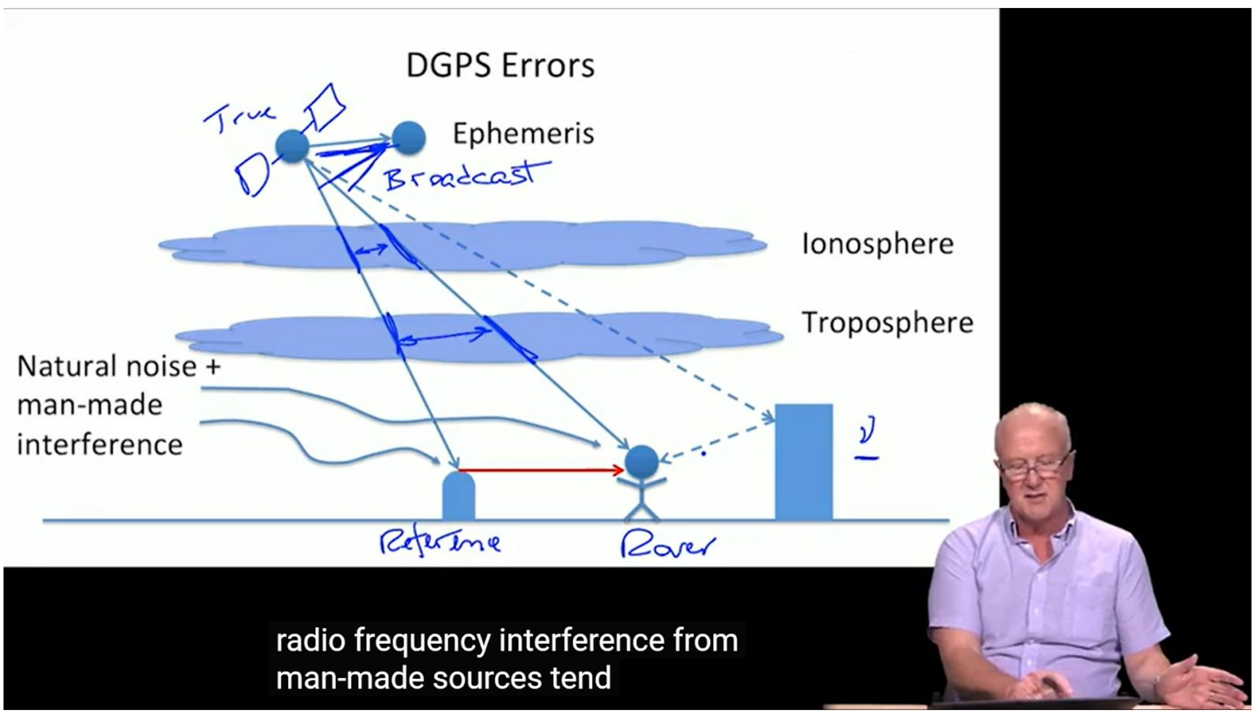

$\tau_U^{(k)} = \left|\underline{x}^{(k)} - \underline{x}_U\right| + I + T + b_U - B^{(k)} + v$ PR
$\tau_0 = \left|\underline{x}^{(k,B)} - \underline{x}_{U,0}\right| + \hat{I} + \hat{T} + b_{U,0} - B^{(k,B)}$ Theo range
$\delta\tau = -\boxed{\Delta\underline{x}_{U,R}} \bullet \underline{1}_U^{(k)} + \delta\underline{x}^{(k)} \bullet \underline{1}_U^{(k)} + \boxed{\delta b_U} - \delta B^{(k)} + \delta I + \delta T + v$
Stand Alon
$\tau_U^{(k)} = \left|\underline{x}^{(k)} - \underline{x}_U\right| + I_U + T_U + b_U - B^{(k)} + v_U$ PR_u
$\tau_R^{(k)} = \left|\underline{x}^{(k)} - \underline{x}_R\right| + I_R + T_R + b_R - B^{(k)} + v_R$ PR_R
DGPS
$\tau_U^{(k)} - \tau_R^{(k)} = \left|\underline{x}^{(k)} - \underline{x}_U\right| - \left|\underline{x}^{(k)} - \underline{x}_R\right| + \Delta I + \Delta T + b_U - b_R + v_U - v_R$
common to both measurement the one at
the user and the one

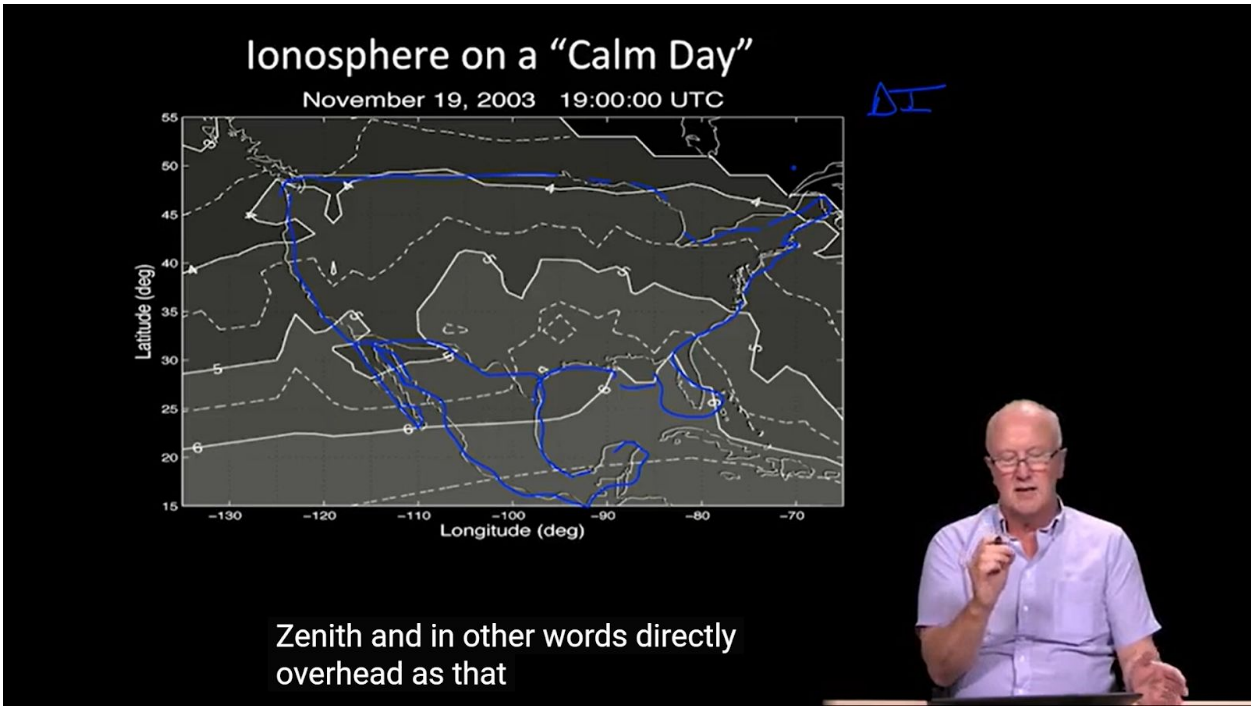

$\left|\underline{x}^{(k)} - \underline{x}_U\right| - \left|\underline{x}^{(k)} - \underline{x}_R\right| = -\Delta\underline{x}_{U,R} \bullet \underline{1}_U^{(k)}$
$\tau_U - \tau_R = \left|\underline{x}^{(k)} - \underline{x}_U\right| - \left|\underline{x}^{(k)} - \underline{x}_R\right| + \Delta I + \Delta T + b_U - b_R + v_U - v_R$
$\tau_U - \tau_R = -\Delta\underline{x}_{U,R} \bullet \underline{1}_U^{(k)} + \Delta I + \Delta T + \Delta b_{U,R} + \Delta v_{U,R}$
$\begin{bmatrix} \tau_U^{(1)} - \tau_R^{(1)} \\ \vdots \\ \tau_U^{(K)} - \tau_R^{(K)} \end{bmatrix} = G \begin{bmatrix} \Delta x_{U,R} \\ \Delta y_{U,R} \\ \Delta z_{U,R} \\ \Delta b_{U,R} \end{bmatrix} + \Delta I + \Delta T + \Delta v_{U,R}$
for the difference in the

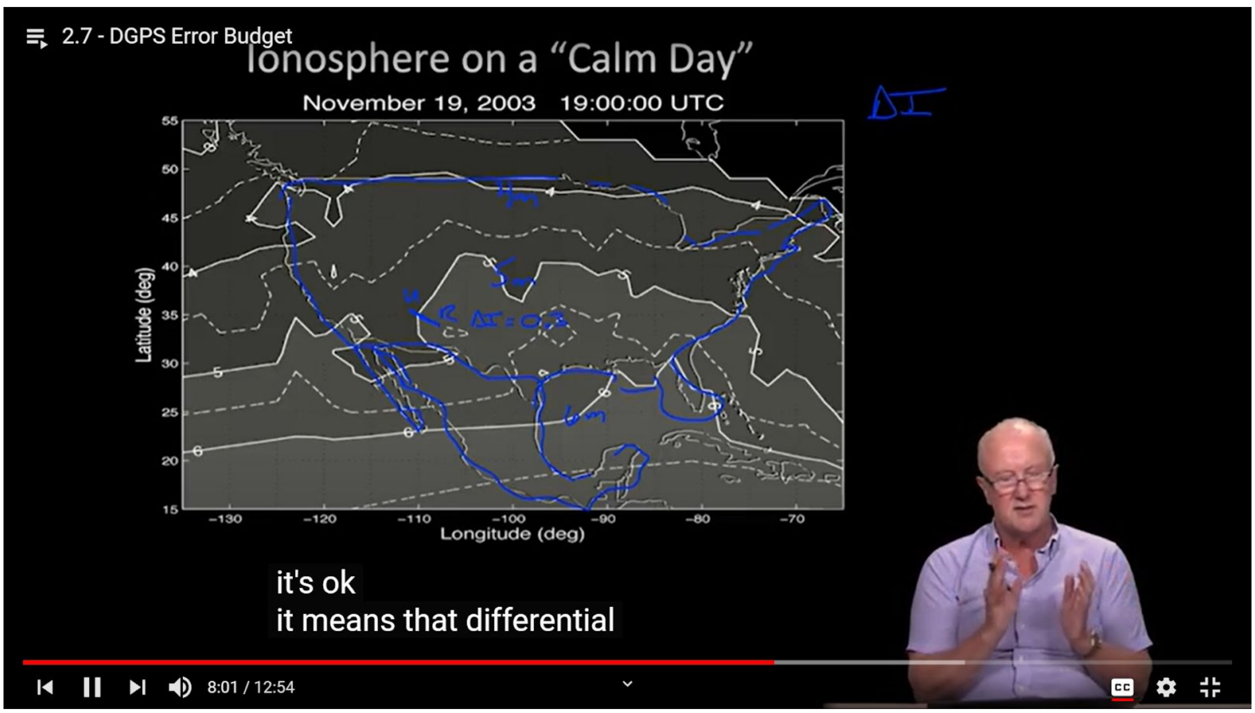

DGPS Errors
Ephemeris
Ionosphere
Troposphere
Natural noise +
man-made
interference

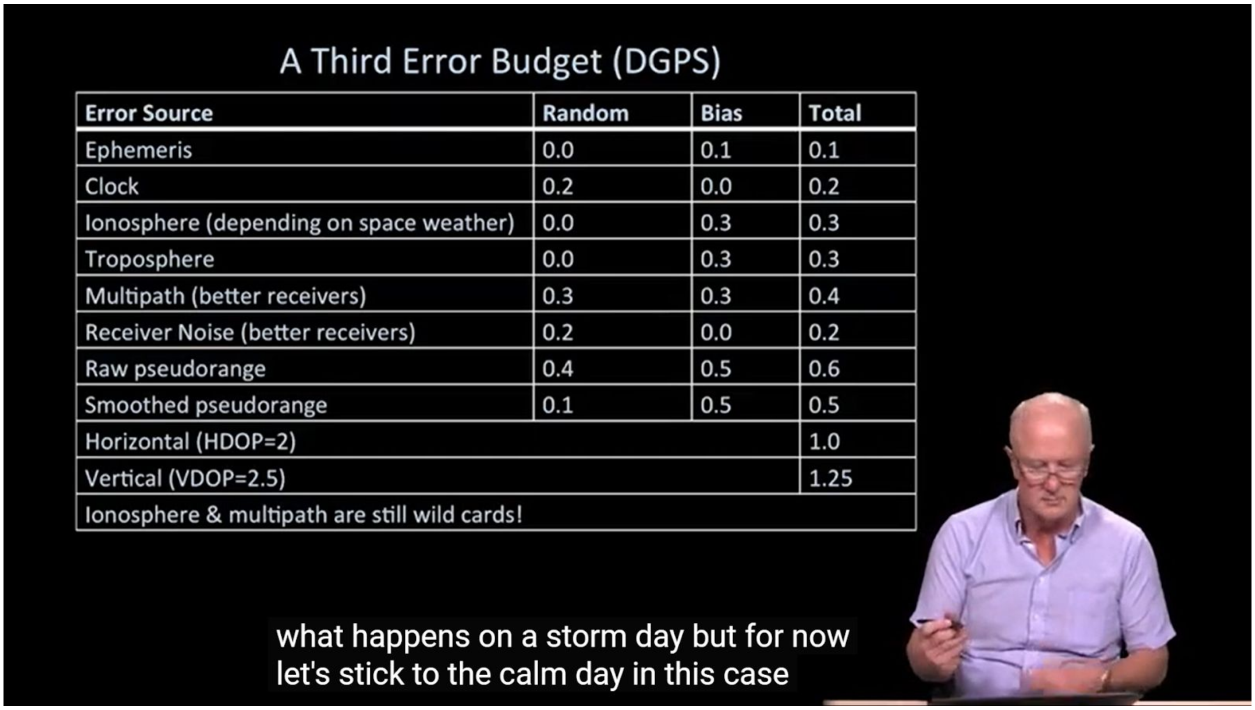

DGPS Errors
True
Ephemeris
Broadcast
Ionosphere
Troposphere
Natural noise +
man-made
interference
Reference
Rover
include the satellite clock perfectly
canceled ephemeris mostly canceled


DGPS Errors
True
Ephemeris
Broadcast
Ionosphere
Troposphere
Natural noise +
man-made
interference
Reference
Rover
canceled ephemeris mostly canceled Ayano
mostly


DGPS Errors
True
Ephemeris
Broadcast
Ionosphere
Troposphere
Natural noise +
man-made
interference
Reference
Rover
radio frequency interference from
man-made sources tend

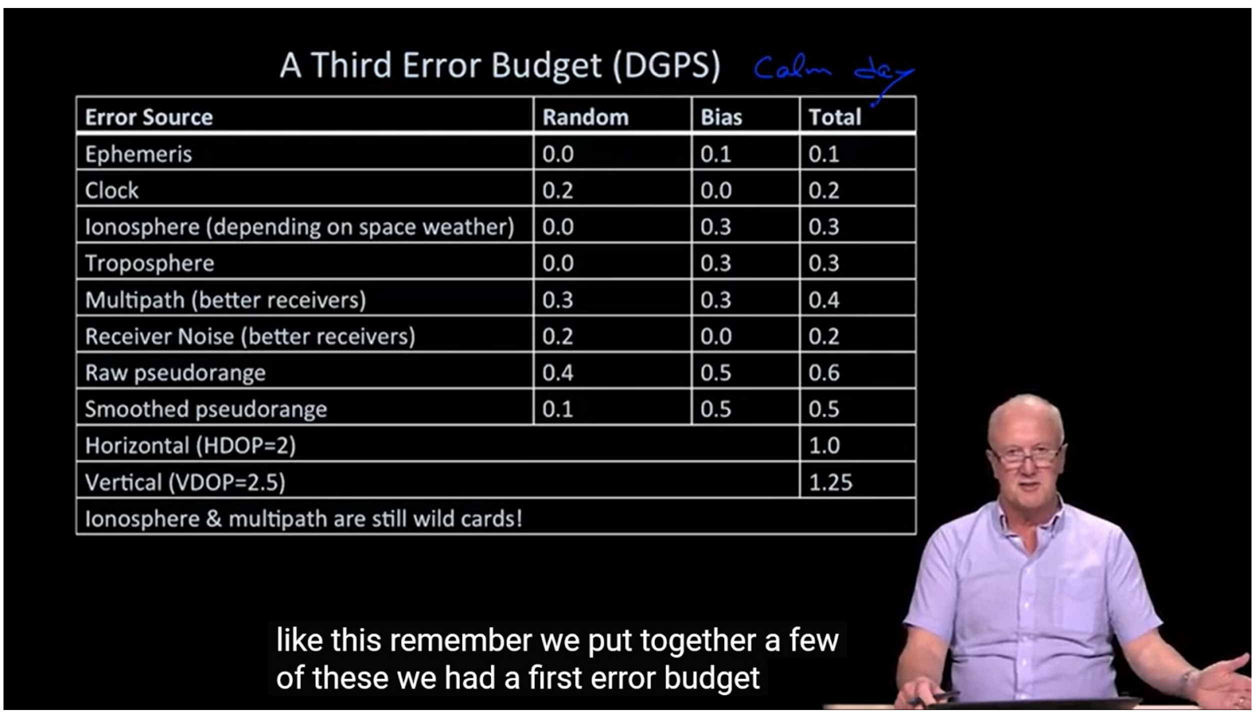

Ionosphere on a "Calm Day"
November 19, 2003 19:00:00 UTC
Latitude (deg)
Longitude (deg)
Zenith and in other words directly
overhead as that


2.7 - DGPS Error Budget
Ionosphere on a "Calm Day"
November 19, 2003 19:00:00 UTC
Latitude (deg)
Longitude (deg)
it's ok
it means that differential
8:01 / 12:54


A Third Error Budget (DGPS)

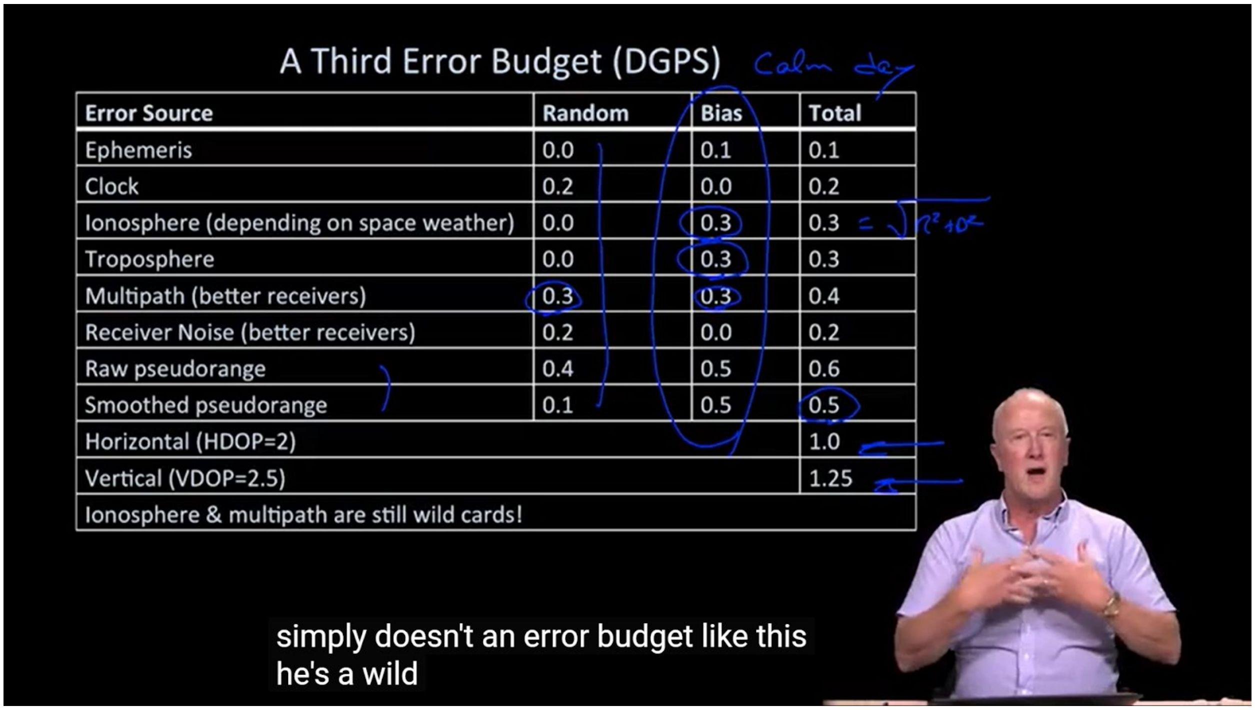
Error Source	Random	Bias	Total
Ephemeris	0.0	0.1	0.1
Clock	0.2	0.0	0.2
Ionosphere (depending on space weather)	0.0	0.3	0.3
Troposphere	0.0	0.3	0.3
Multipath (better receivers)	0.3	0.3	0.4
Receiver Noise (better receivers)	0.2	0.0	0.2
Raw pseudorange	0.4	0.5	0.6
Smoothed pseudorange	0.1	0.5	0.5
Horizontal (HDOP=2)			1.0
Vertical (VDOP=2.5)			1.25
Ionosphere & multipath are still wild cards!			

what happens on a storm day but for now
let's stick to the calm day in this case


A Third Error Budget (DGPS)
Calm day

Error Source	Random	Bias	Total
Ephemeris	0.0	0.1	0.1
Clock	0.2	0.0	0.2
Ionosphere (depending on space weather)	0.0	0.3	0.3
Troposphere	0.0	0.3	0.3
Multipath (better receivers)	0.3	0.3	0.4
Receiver Noise (better receivers)	0.2	0.0	0.2
Raw pseudorange	0.4	0.5	0.6
Smoothed pseudorange	0.1	0.5	0.5
Horizontal (HDOP=2)			1.0
Vertical (VDOP=2.5)			1.25
Ionosphere & multipath are still wild cards!			

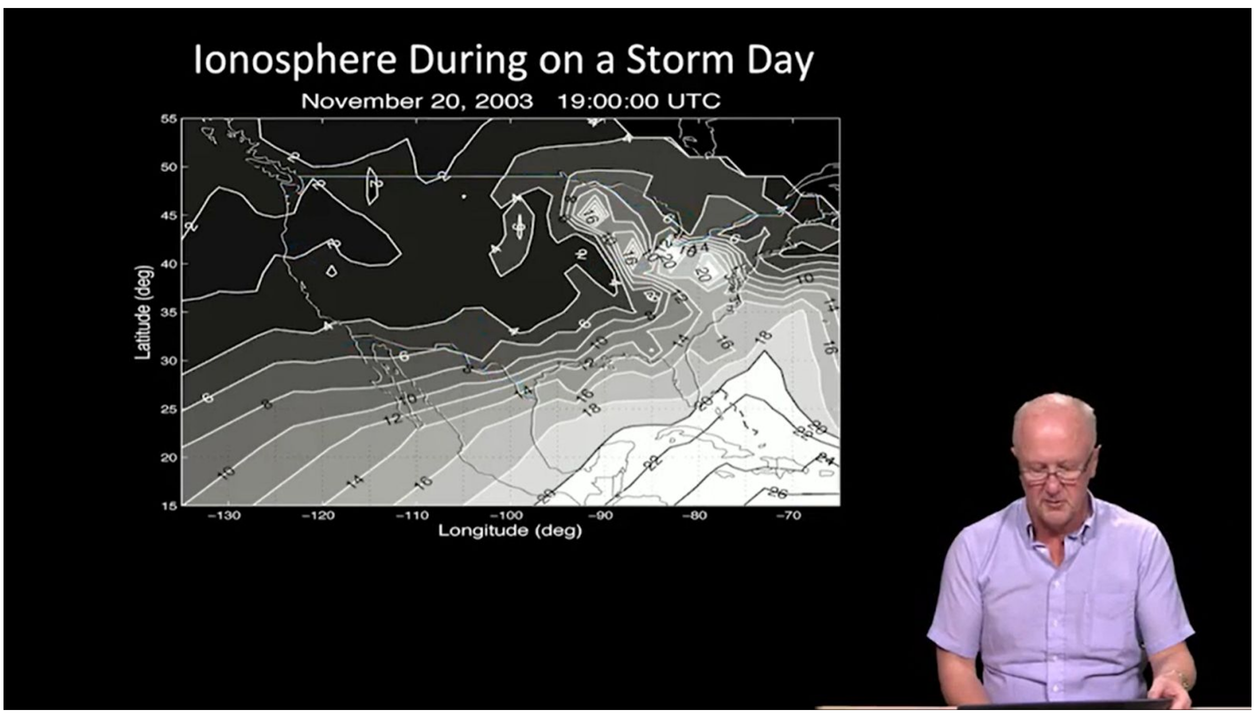
like this remember we put together a few
of these we had a first error budget

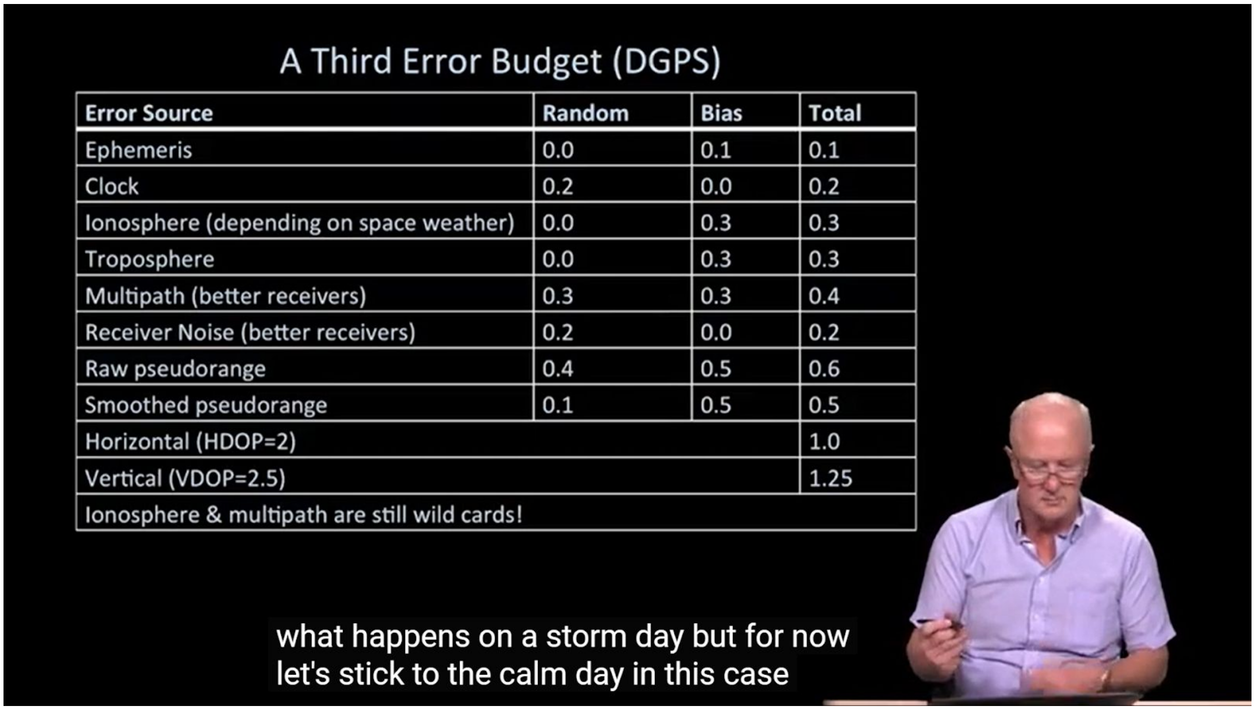


A Third Error Budget (DGPS)

Calm day

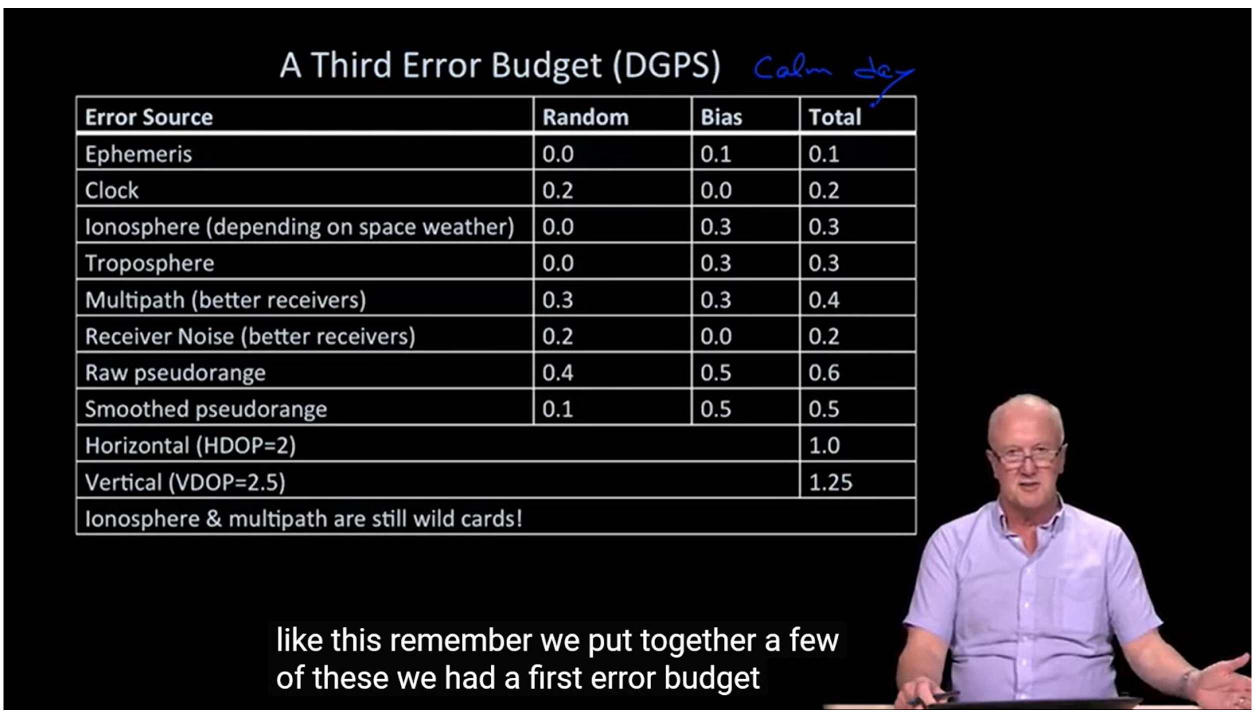
Error Source	Random	Bias	Total
Ephemeris	0.0	0.1	0.1
Clock	0.2	0.0	0.2
Ionosphere (depending on space weather)	0.0	0.3	0.3 $= \sqrt{r^2+b^2}$
Troposphere	0.0	0.3	0.3
Multipath (better receivers)	0.3	0.3	0.4
Receiver Noise (better receivers)	0.2	0.0	0.2
Raw pseudorange	0.4	0.5	0.6
Smoothed pseudorange	0.1	0.5	0.5
Horizontal (HDOP=2)			1.0
Vertical (VDOP=2.5)			1.25
Ionosphere & multipath are still wild cards!			




A Third Error Budget (DGPS)

Error Source	Random	Bias	Total
Ephemeris	0.0	0.1	0.1
Clock	0.2	0.0	0.2
Ionosphere (depending on space weather)	0.0	0.3	0.3
Troposphere	0.0	0.3	0.3
Multipath (better receivers)	0.3	0.3	0.4
Receiver Noise (better receivers)	0.2	0.0	0.2
Raw pseudorange	0.4	0.5	0.6
Smoothed pseudorange	0.1	0.5	0.5
Horizontal (HDOP=2)			1.0
Vertical (VDOP=2.5)			1.25
Ionosphere & multipath are still wild cards!			

what happens on a storm day but for now
let's stick to the calm day in this case


A Third Error Budget (DGPS) Calm day

Error Source	Random	Bias	Total
Ephemeris	0.0	0.1	0.1
Clock	0.2	0.0	0.2
Ionosphere (depending on space weather)	0.0	0.3	0.3
Troposphere	0.0	0.3	0.3
Multipath (better receivers)	0.3	0.3	0.4
Receiver Noise (better receivers)	0.2	0.0	0.2
Raw pseudorange	0.4	0.5	0.6
Smoothed pseudorange	0.1	0.5	0.5
Horizontal (HDOP=2)			1.0
Vertical (VDOP=2.5)			1.25
Ionosphere & multipath are still wild cards!			

like this remember we put together a few
of these we had a first error budget

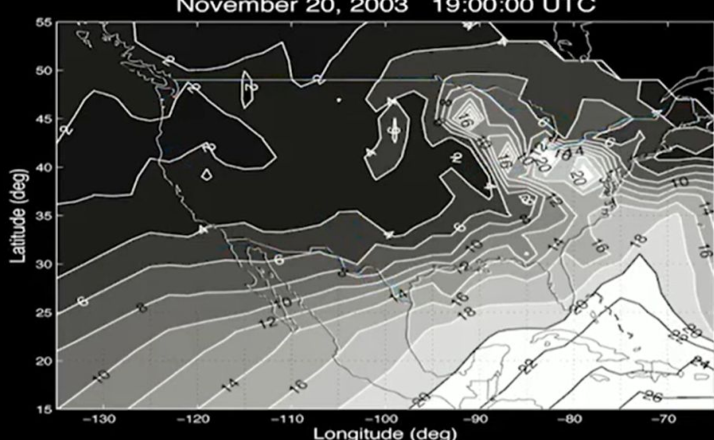
A Third Error Budget (DGPS)

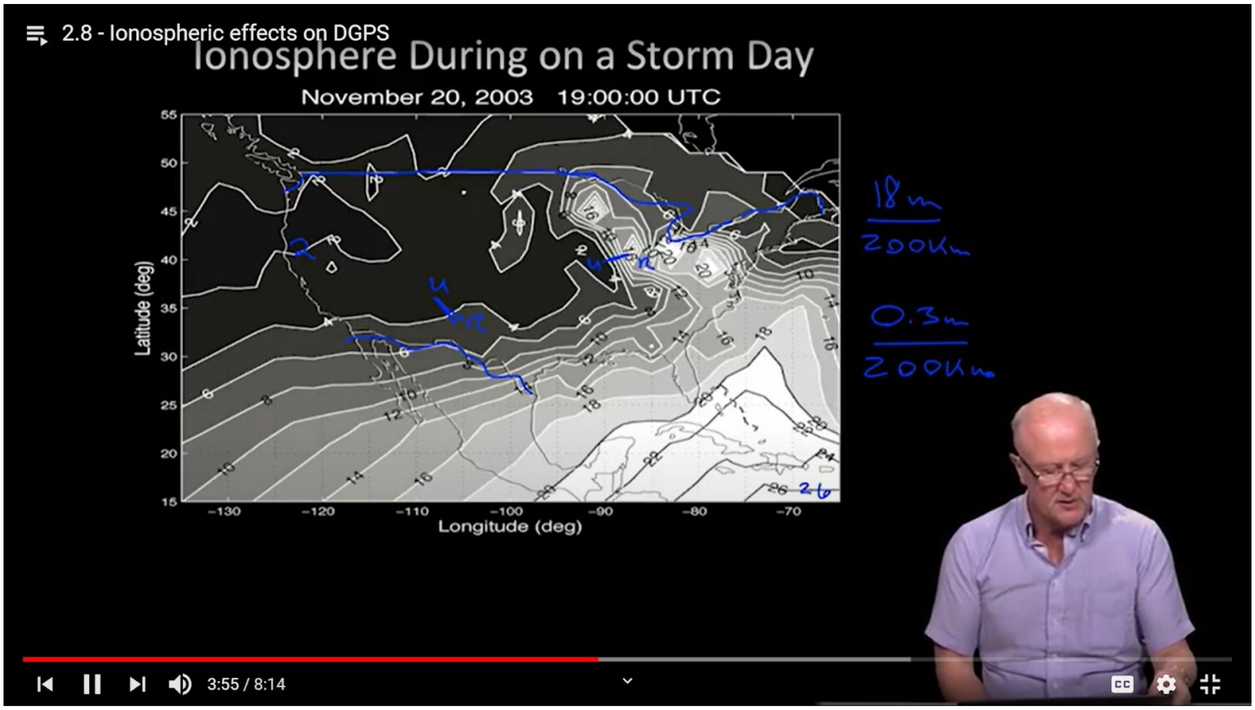
Calm day

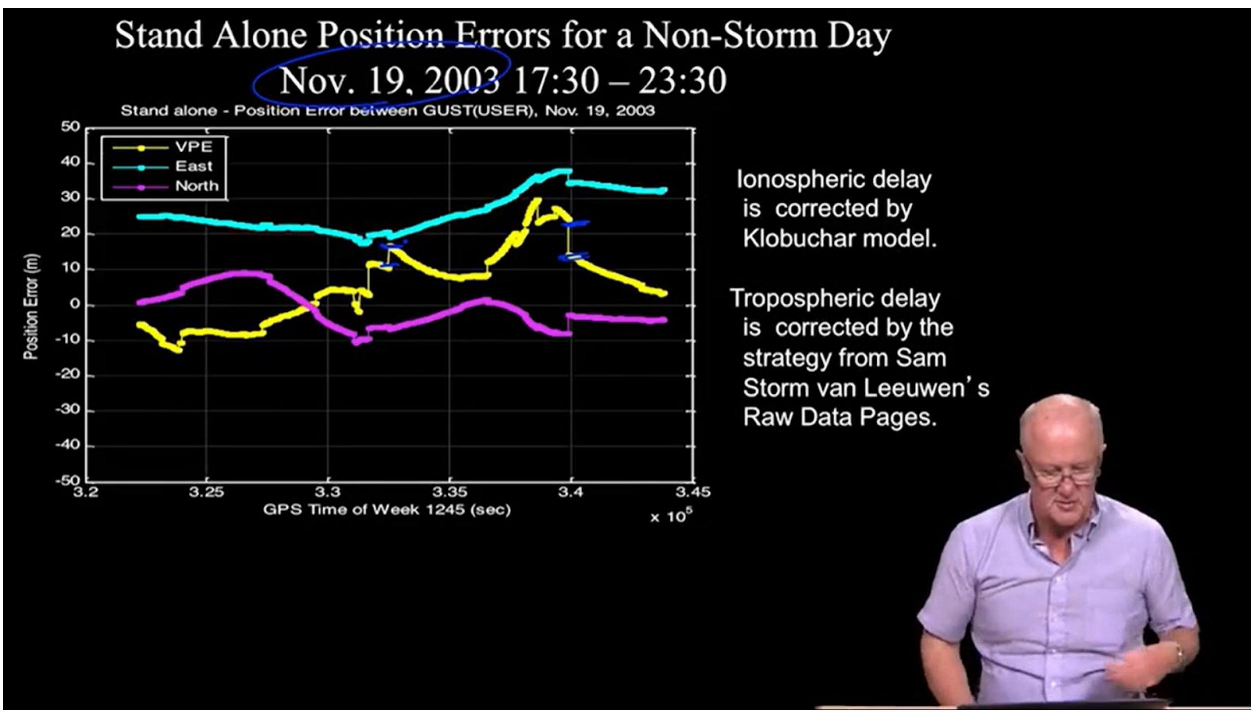
Error Source	Random	Bias	Total
Ephemeris	0.0	0.1	0.1
Clock	0.2	0.0	0.2
Ionosphere (depending on space weather)	0.0	0.3	0.3 $= \sqrt{r^2+b^2}$
Troposphere	0.0	0.3	0.3
Multipath (better receivers)	0.3	0.3	0.4
Receiver Noise (better receivers)	0.2	0.0	0.2
Raw pseudorange	0.4	0.5	0.6
Smoothed pseudorange	0.1	0.5	0.5
Horizontal (HDOP=2)			1.0
Vertical (VDOP=2.5)			1.25
Ionosphere & multipath are still wild cards!			

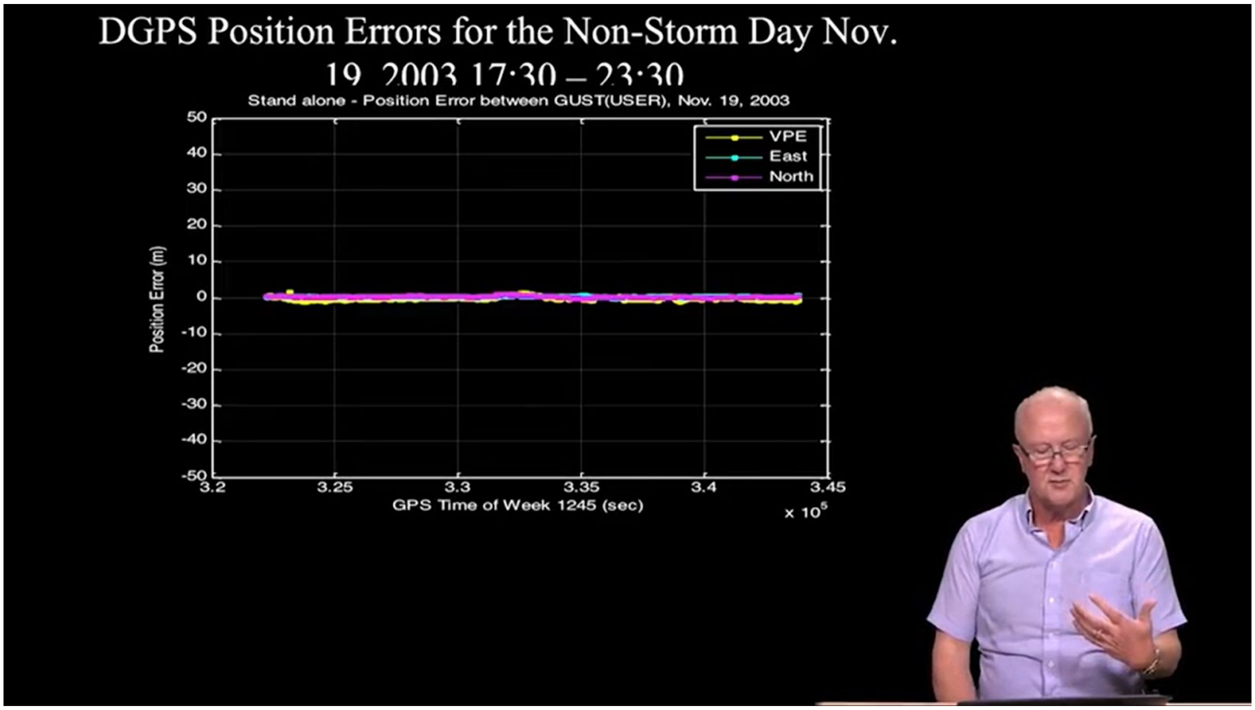
simply doesn't an error budget like this
he's a wild

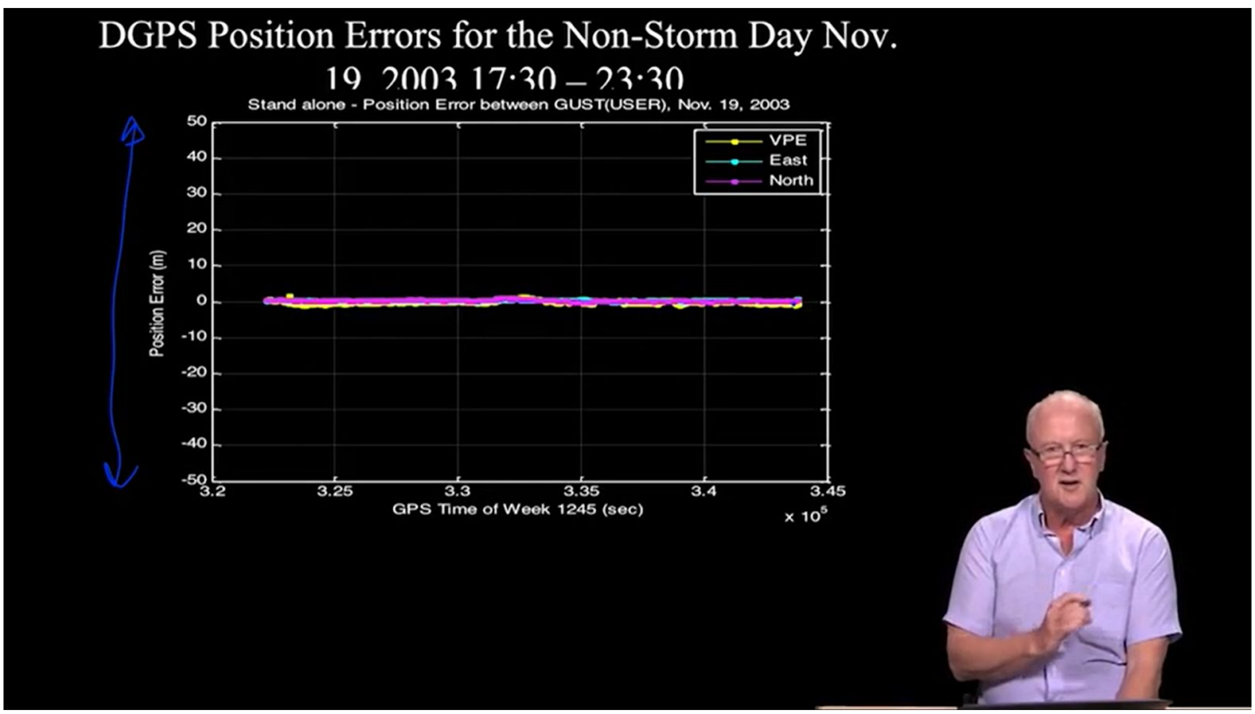
Ionosphere During on a Storm Day

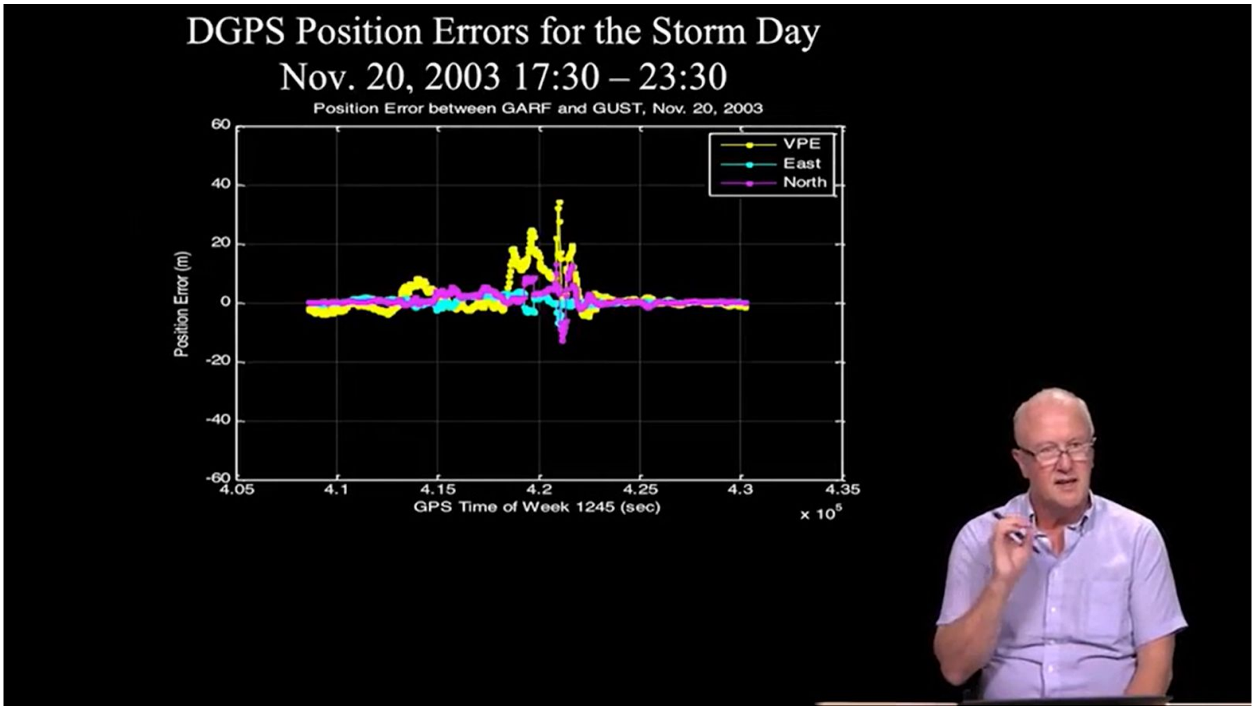


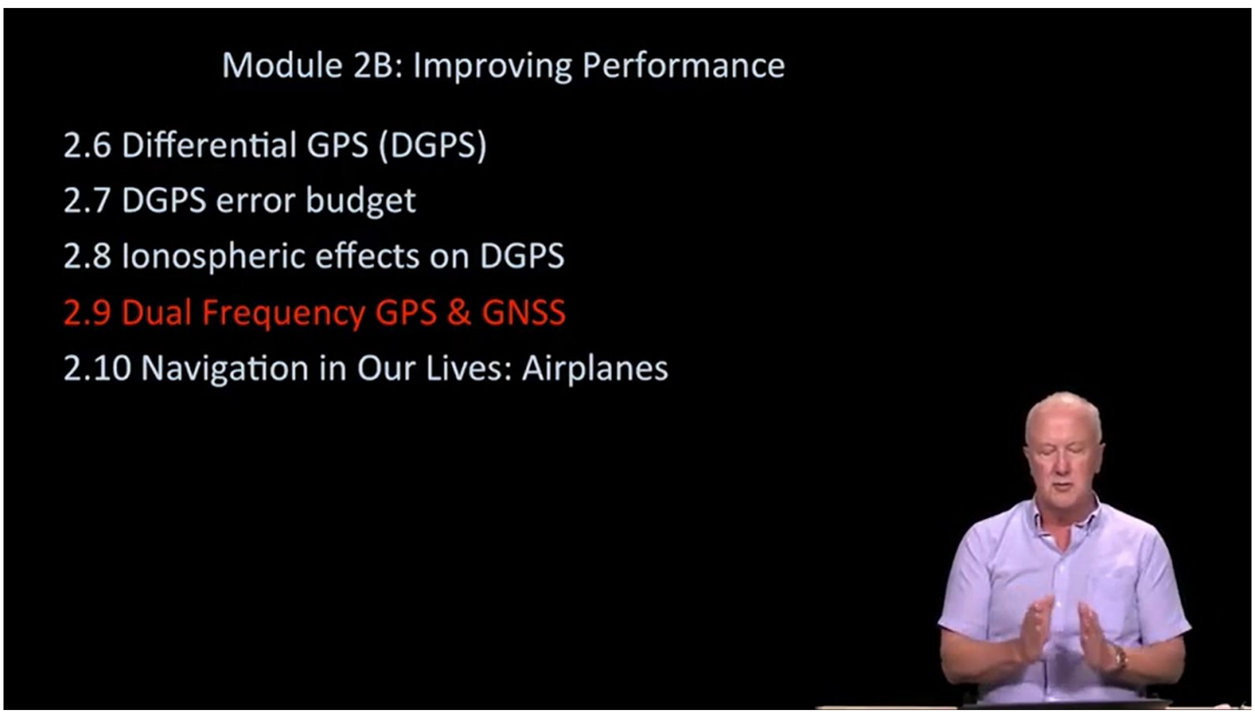

2.8 - Ionospheric effects on DGPS
Ionosphere During on a Storm Day
November 20, 2003 19:00:00 UTC
Latitude (deg)
Longitude (deg)
18m
200Km
0.3m
200Km
3:55 / 8:14

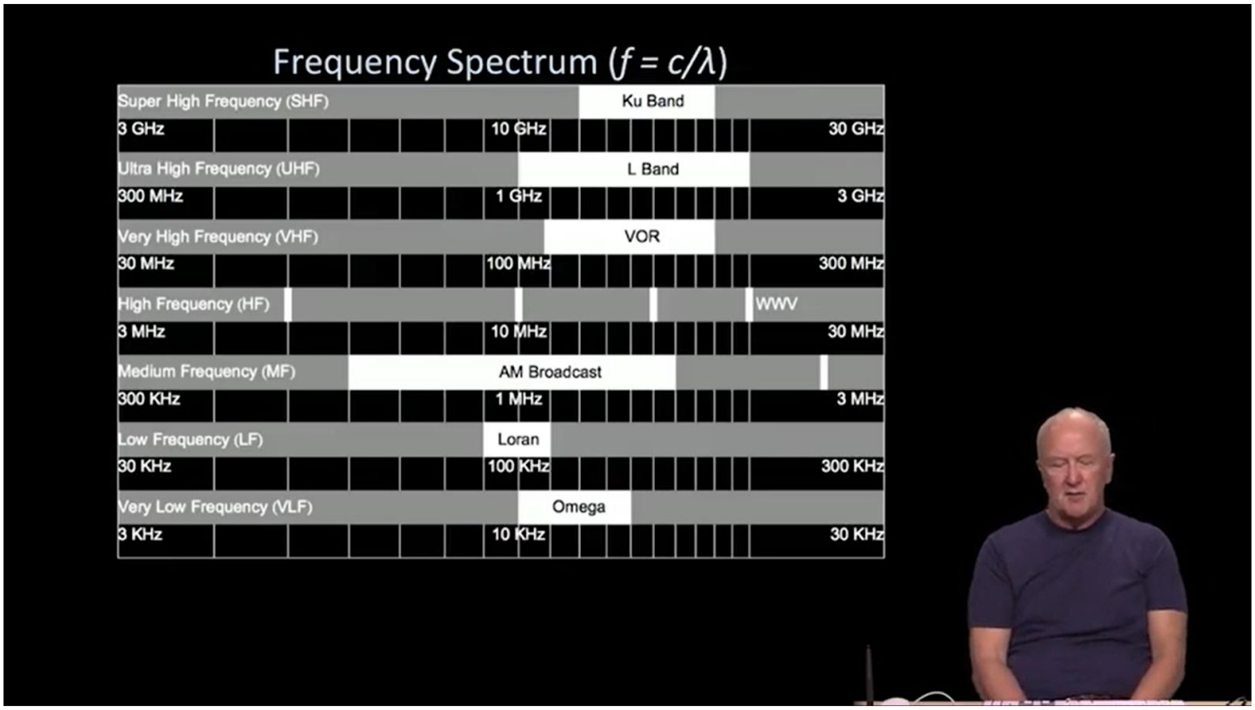

Stand Alone Position Errors for a Non-Storm Day
Nov. 19, 2003 17:30 – 23:30
Stand alone - Position Error between GUST(USER), Nov. 19, 2003
VPE
East
North
Position Error (m)
GPS Time of Week 1245 (sec)
x 10^5
Ionospheric delay is corrected by Klobuchar model.
Tropospheric delay is corrected by the strategy from Sam Storm van Leeuwen's Raw Data Pages.

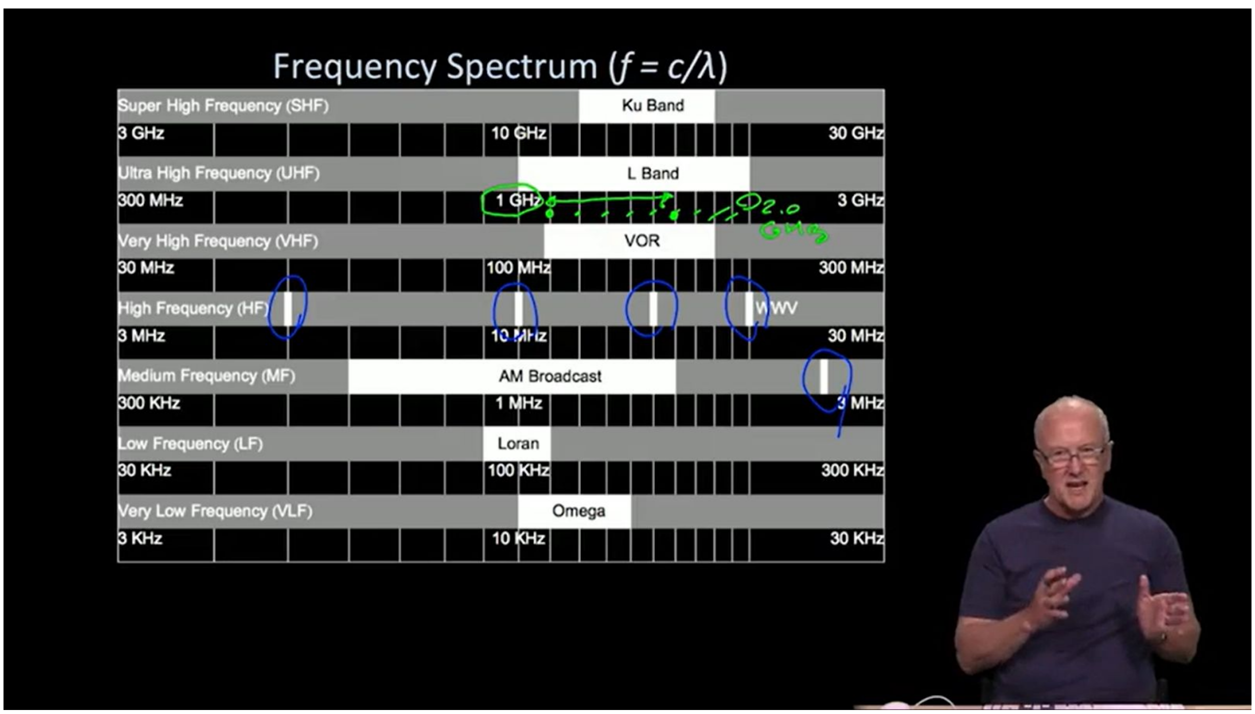

DGPS Position Errors for the Non-Storm Day Nov. 19, 2003 17:30 – 23:30
Stand alone - Position Error between GUST(USER), Nov. 19, 2003
VPE
East
North
Position Error (m)
GPS Time of Week 1245 (sec)
x 10^5

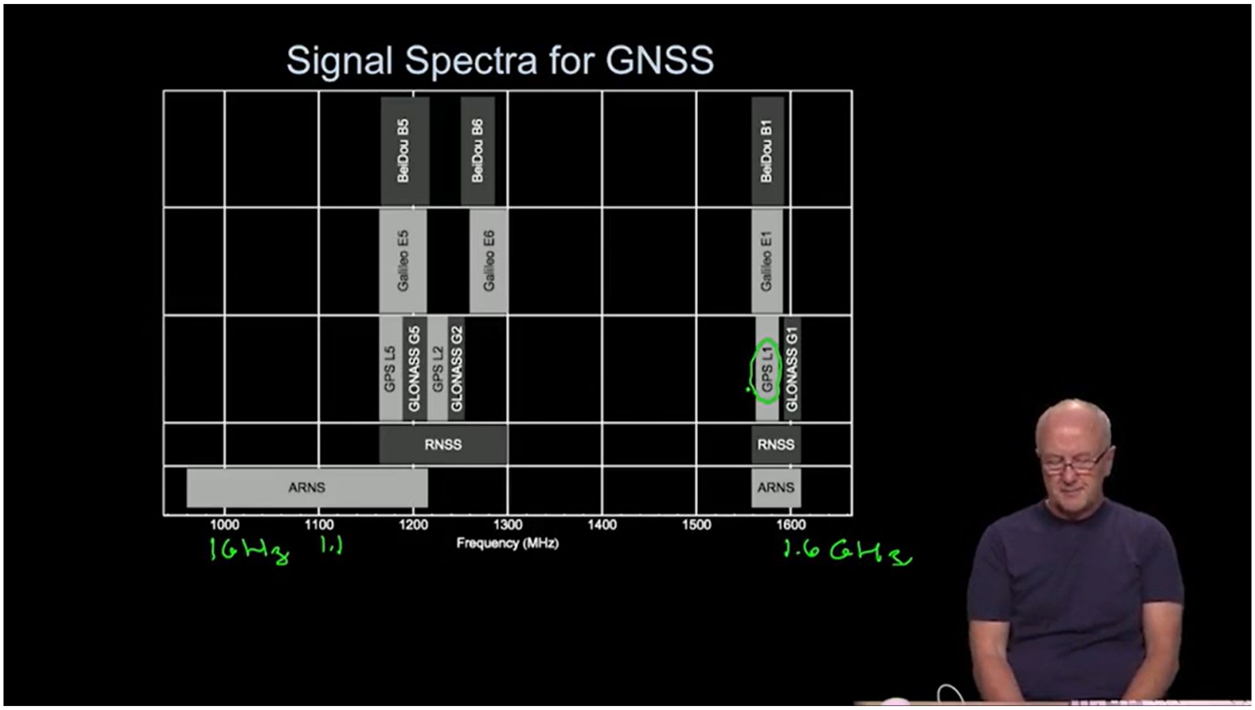

DGPS Position Errors for the Non-Storm Day Nov. 19, 2003 17:30 – 23:30
Stand alone - Position Error between GUST(USER), Nov. 19, 2003
VPE
East
North
Position Error (m)
GPS Time of Week 1245 (sec)
x 10^5

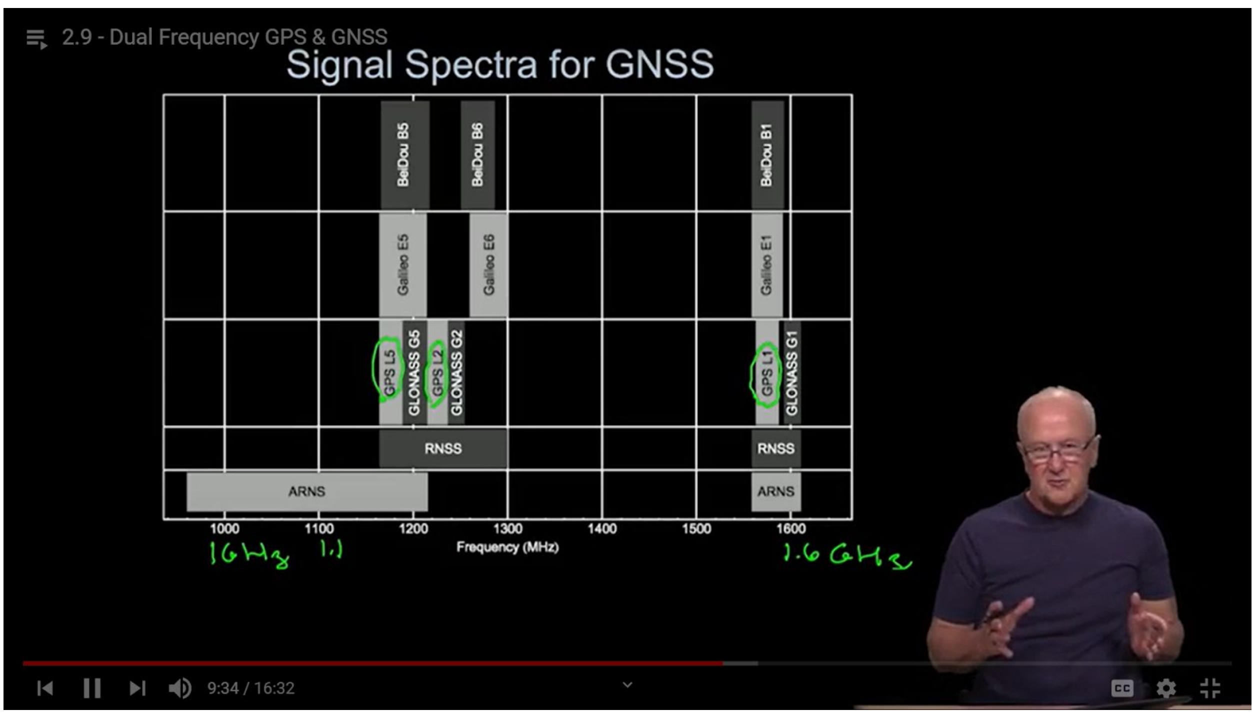

DGPS Position Errors for the Storm Day
Nov. 20, 2003 17:30 – 23:30
Position Error between GARF and GUST, Nov. 20, 2003
VPE
East
North
Position Error (m)
60
40
20
0
-20
-40
-60
4.05
4.1
4.15
4.2
4.25
4.3
4.35
GPS Time of Week 1245 (sec)
x 10^5


Module 2B: Improving Performance
2.6 Differential GPS (DGPS)
2.7 DGPS error budget
2.8 Ionospheric effects on DGPS
2.9 Dual Frequency GPS & GNSS
2.10 Navigation in Our Lives: Airplanes

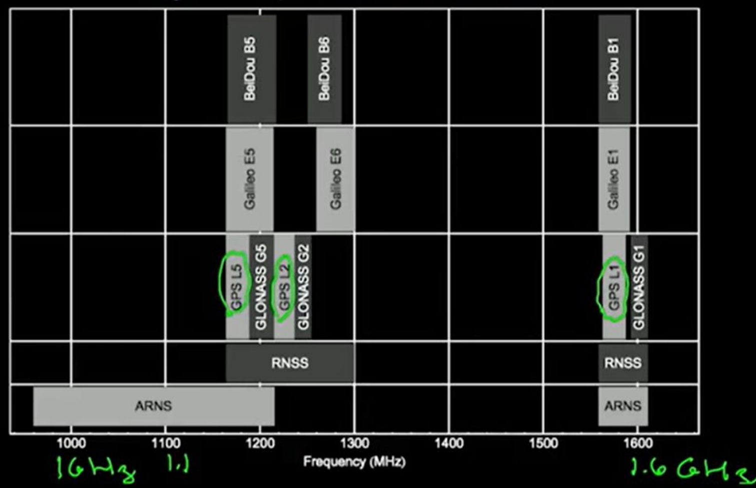

Frequency Spectrum ($f = c/\lambda$)
Super High Frequency (SHF)
Ku Band
3 GHz
10 GHz
30 GHz
Ultra High Frequency (UHF)
L Band
300 MHz
1 GHz
3 GHz
Very High Frequency (VHF)
VOR
30 MHz
100 MHz
300 MHz
High Frequency (HF)
WWV
3 MHz
10 MHz
30 MHz
Medium Frequency (MF)
AM Broadcast
300 KHz
1 MHz
3 MHz
Low Frequency (LF)
Loran
30 KHz
100 KHz
300 KHz
Very Low Frequency (VLF)
Omega
3 KHz
10 KHz
30 KHz


Frequency Spectrum ($f = c/\lambda$)
Super High Frequency (SHF)
Ku Band
3 GHz
10 GHz
30 GHz
Ultra High Frequency (UHF)
L Band
300 MHz
1 GHz
2.0 GHz
3 GHz
Very High Frequency (VHF)
VOR
30 MHz
100 MHz
300 MHz
High Frequency (HF)
WWV
3 MHz
10 MHz
30 MHz
Medium Frequency (MF)
AM Broadcast
300 KHz
1 MHz
3 MHz
Low Frequency (LF)
Loran
30 KHz
100 KHz
300 KHz
Very Low Frequency (VLF)
Omega
3 KHz
10 KHz
30 KHz


Signal Spectra for GNSS
BeiDou B5
BeiDou B6
BeiDou B1
Galileo E5
Galileo E6
Galileo E1
GPS L5
GLONASS G5
GPS L2
GLONASS G2
GPS L1
GLONASS G1
RNSS
RNSS
ARNS
ARNS
1000
1100
1200
1300
1400
1500
1600
Frequency (MHz)
1GHz
1.1
1.6 GHz


2.9 - Dual Frequency GPS & GNSS
Signal Spectra for GNSS
BeiDou B5
BeiDou B6
BeiDou B1
Galileo E5
Galileo E6
Galileo E1
GPS L5
GLONASS G5
GPS L2
GLONASS G2
GPS L1
GLONASS G1
RNSS
RNSS
ARNS
ARNS
1000
1100
1200
1300
1400
1500
1600
Frequency (MHz)
1GHz
1.1
1.6 GHz
9:34 / 16:32

Signal Spectra for GNSS



Dual Frequency for Ionospheric Measurement

Ionospheric errors are around 10 - 20 meters

Single frequency users use a model to cut the error in half.

Dual frequency users can measure the ionosphere in real time.

$\tau_{L1} = \rho + \frac{40.3TEC}{f_{L1}^2}$ meters and $\tau_{L2} = \rho + \frac{40.3TEC}{f_{L2}^2}$ meters

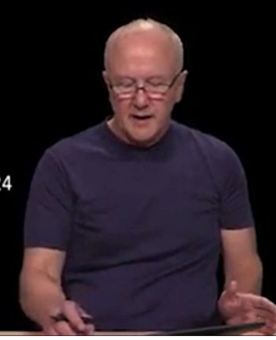
I_{L1} I_{L2}

$\tau_{\text{iono-free}} = \alpha\tau_{L1} + \beta\tau_{L2}$

where $\alpha + \beta = 1$ and $\alpha\frac{40.3TEC}{f_{L1}^2} + \beta\frac{40.3TEC}{f_{L2}^2} = 0$

$\alpha = 2.54573$ and $\beta = -1.54573$

24



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1227.60×10^6

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24

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1227.60×10^6

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1227.60 x10⁶

$\tau_{\text{iono-free}} = \alpha\tau_{L1} + \beta\tau_{L2}$

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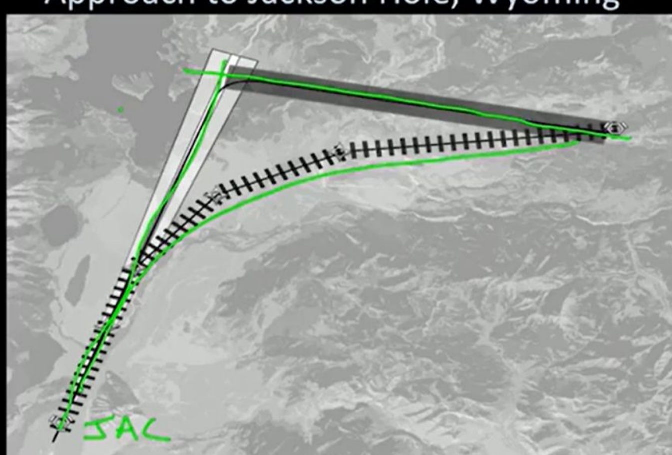
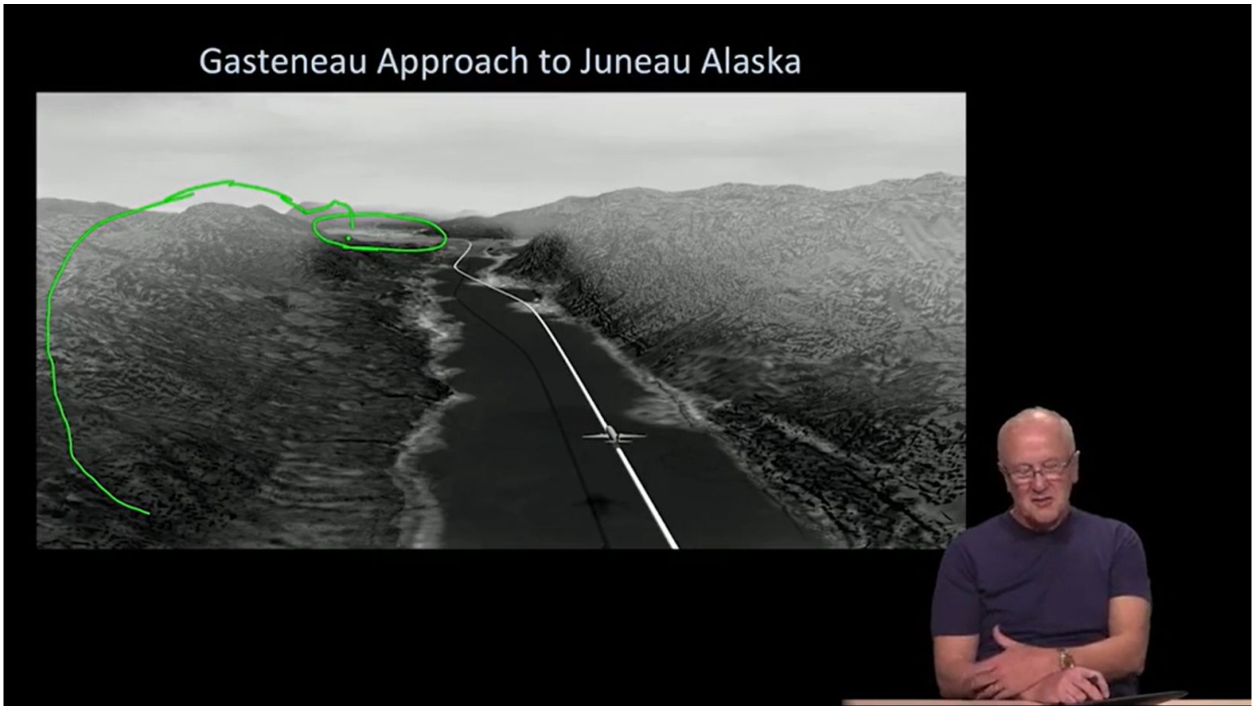
$\alpha = 2.54573$ and $\beta = -1.54573$

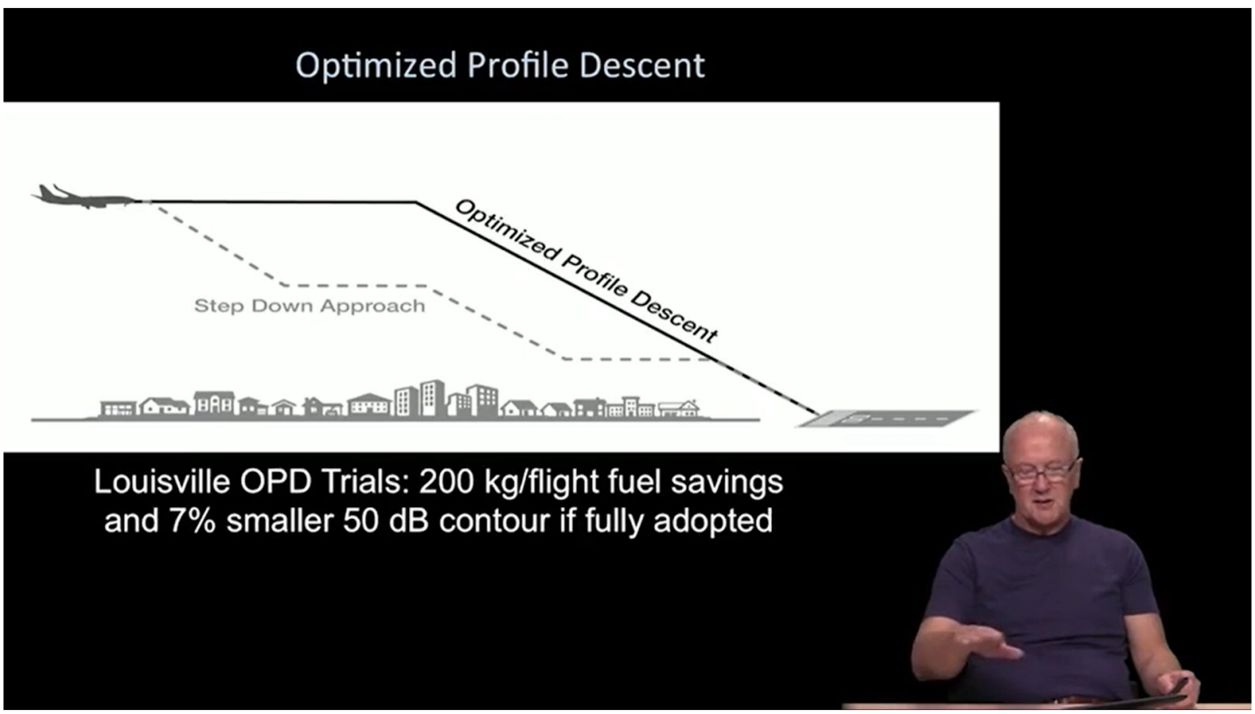
1575.42 x10⁶

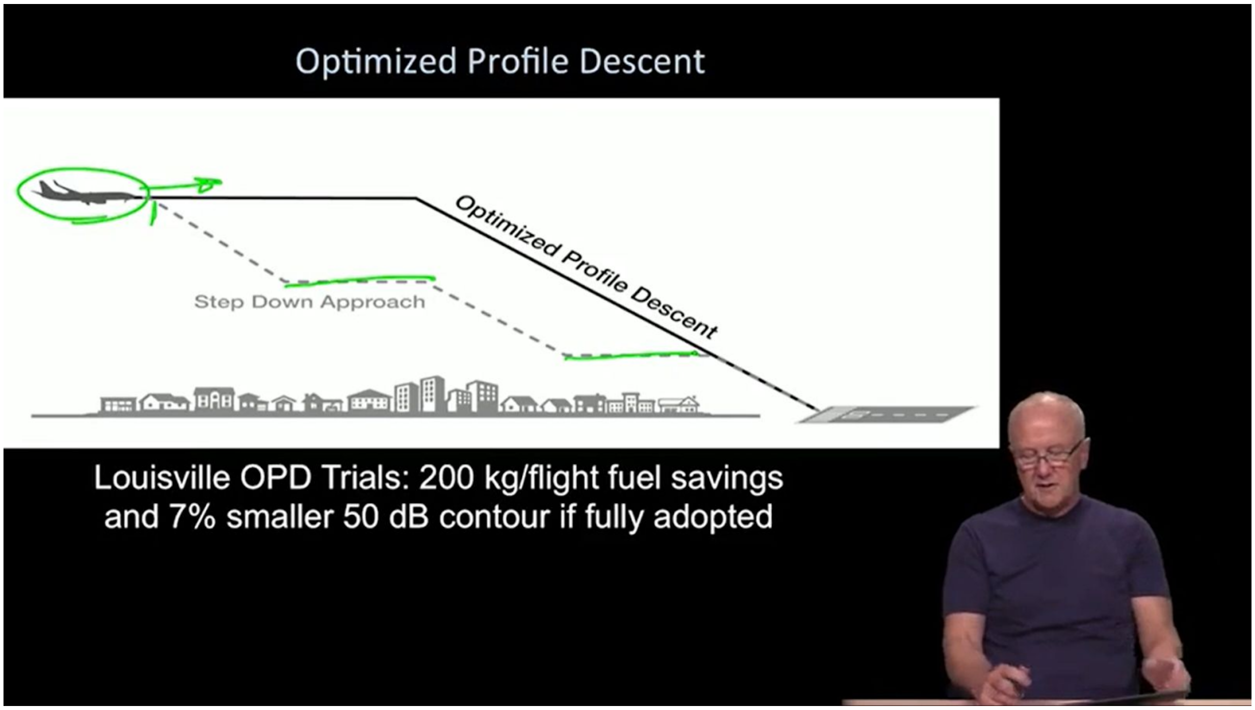
24

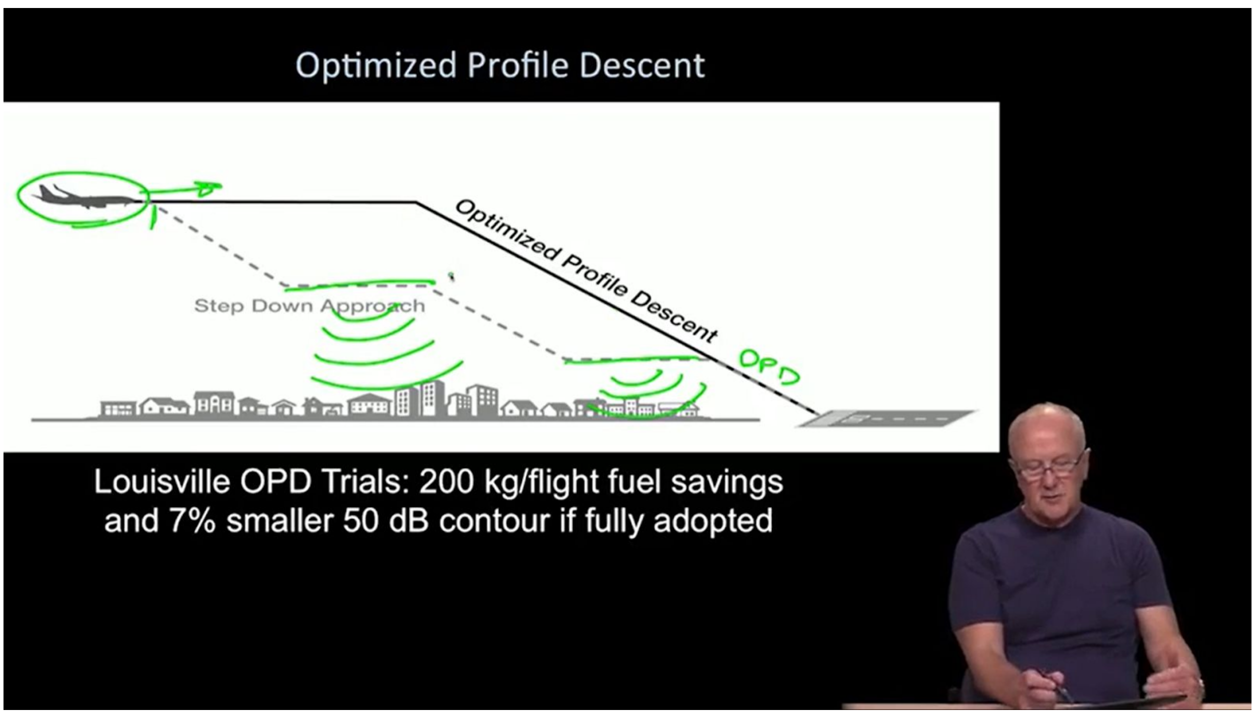
Approach to Jackson Hole, Wyoming

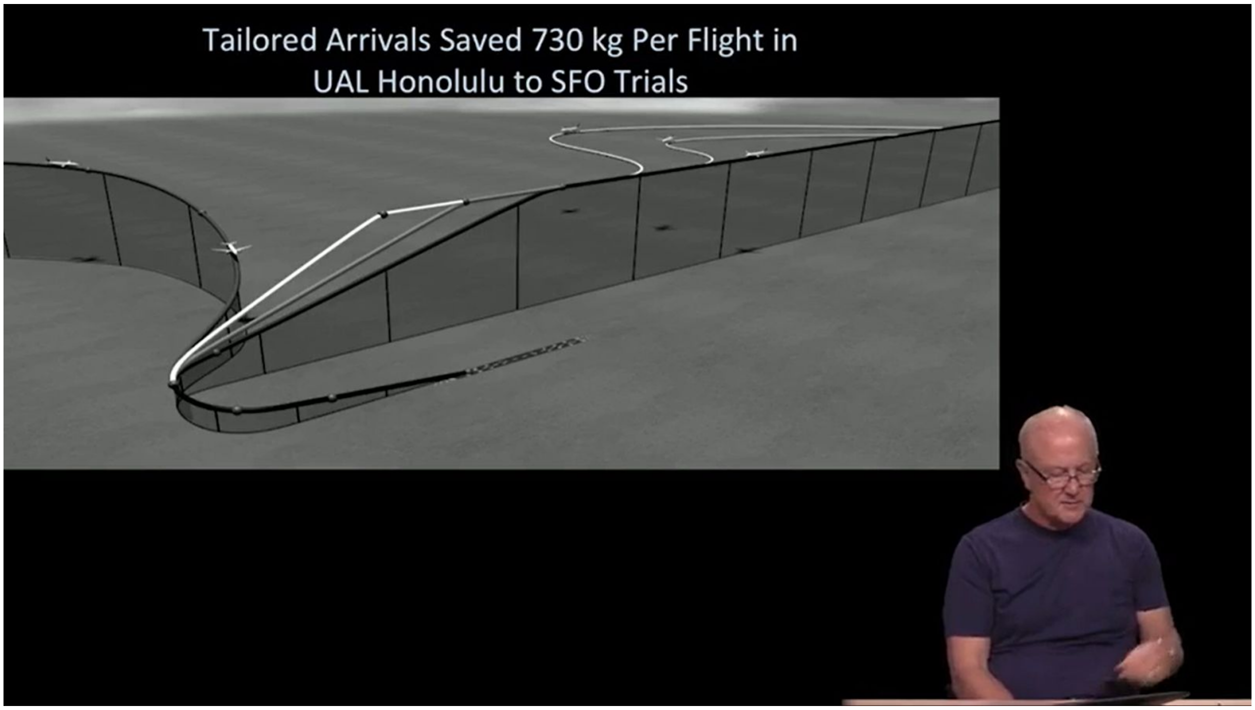


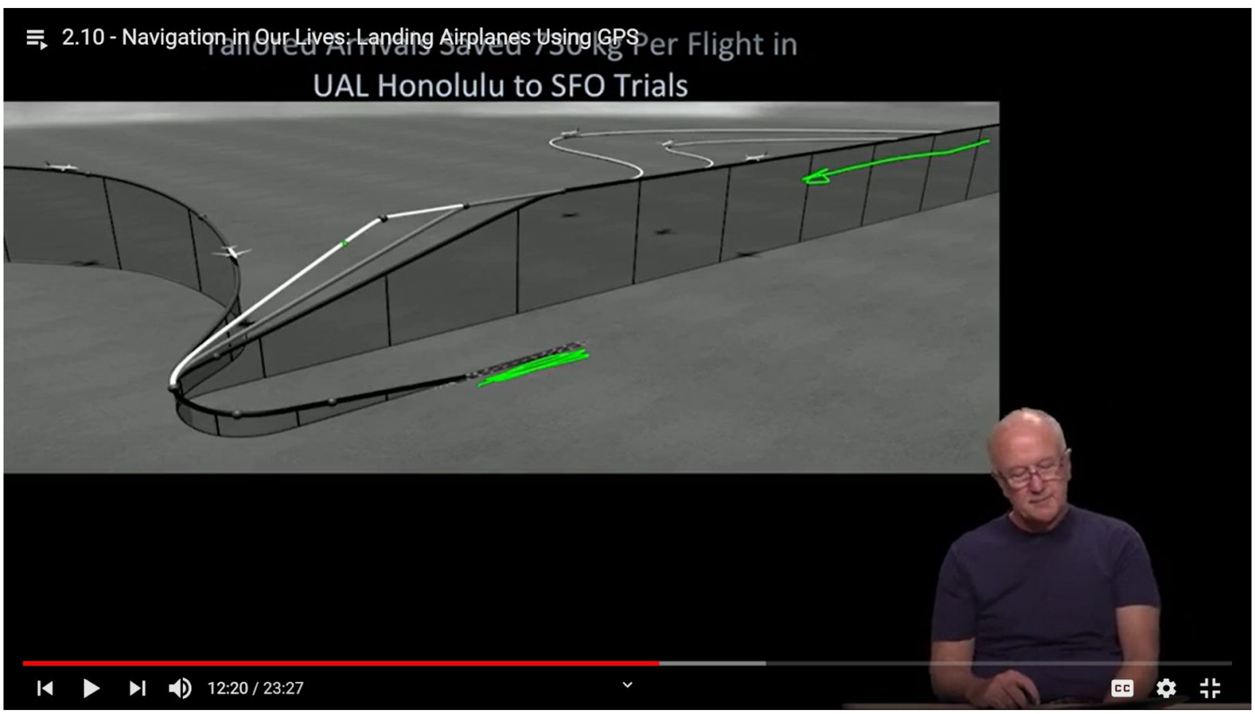

Gasteneau Approach to Juneau Alaska

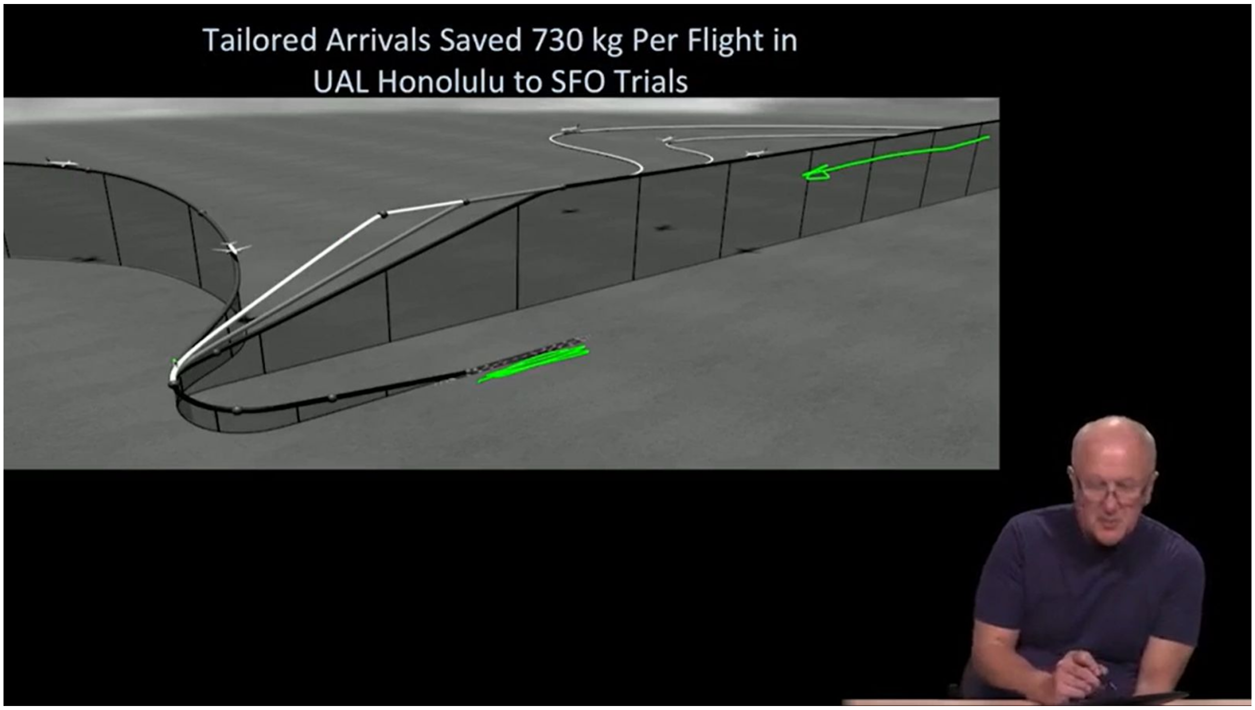

Optimized Profile Descent
Optimized Profile Descent
Step Down Approach
Louisville OPD Trials: 200 kg/flight fuel savings and 7% smaller 50 dB contour if fully adopted

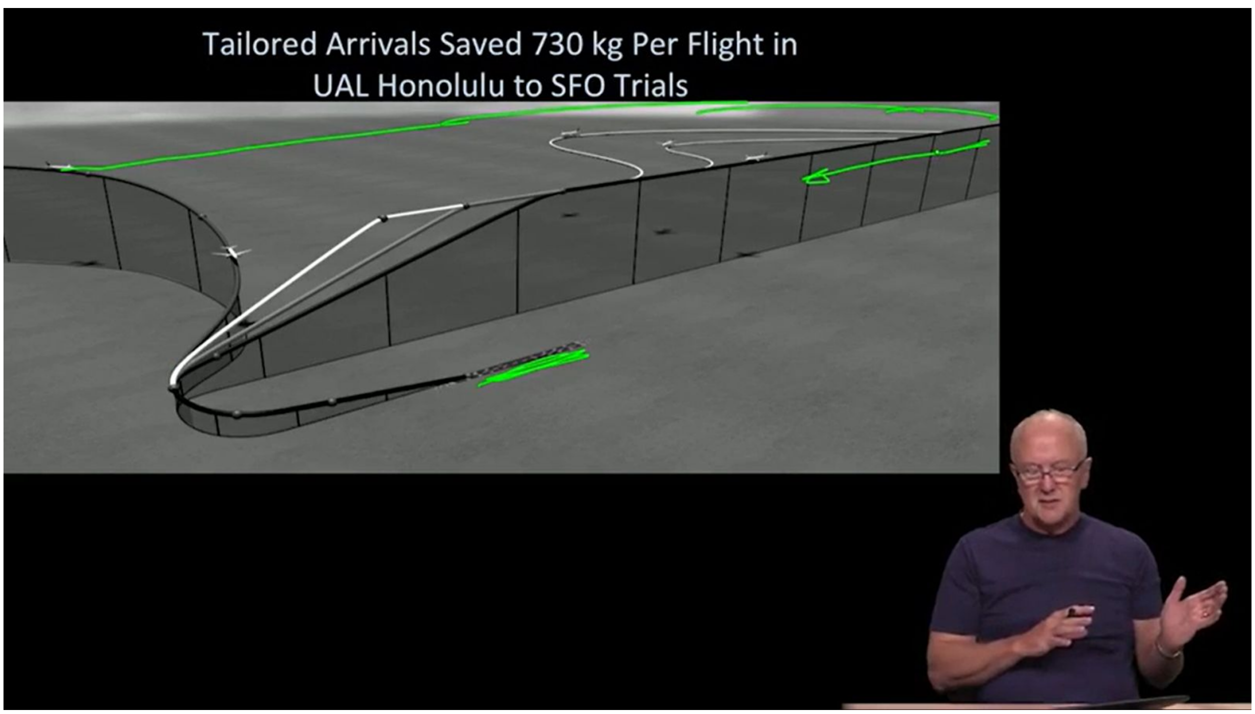

Optimized Profile Descent
Optimized Profile Descent
Step Down Approach
Louisville OPD Trials: 200 kg/flight fuel savings
and 7% smaller 50 dB contour if fully adopted

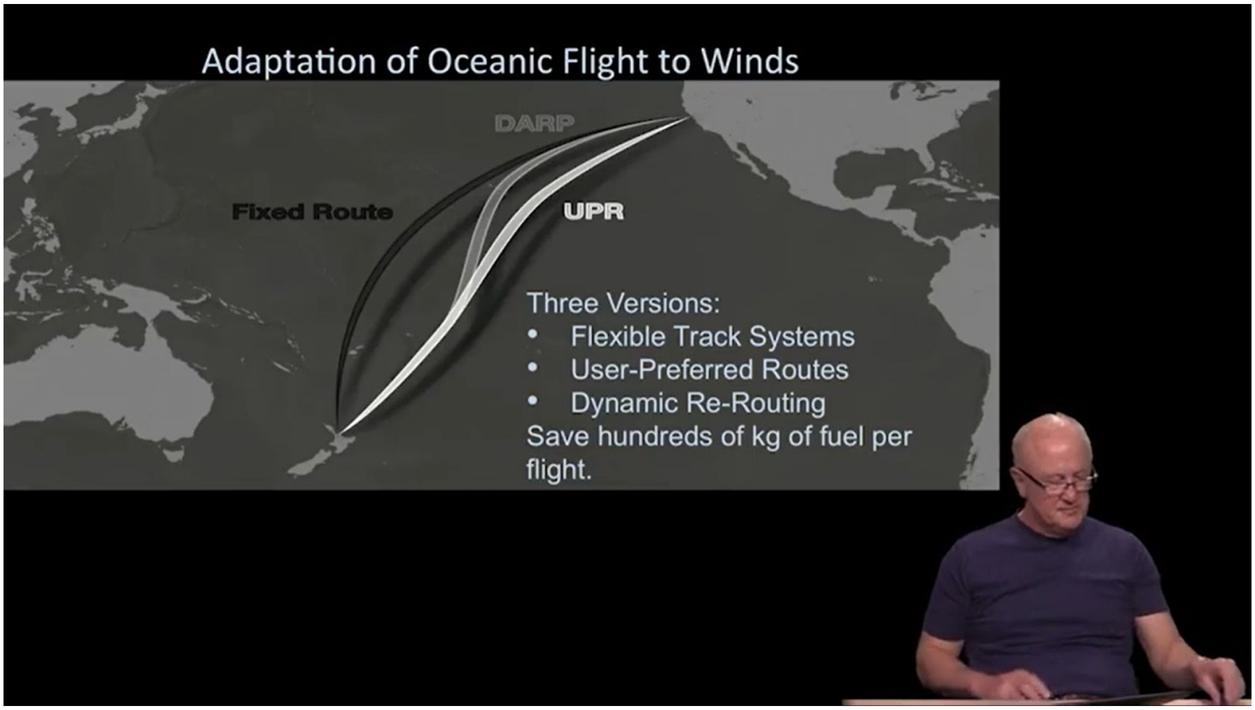

Optimized Profile Descent
Optimized Profile Descent
Step Down Approach
OPD
Louisville OPD Trials: 200 kg/flight fuel savings
and 7% smaller 50 dB contour if fully adopted

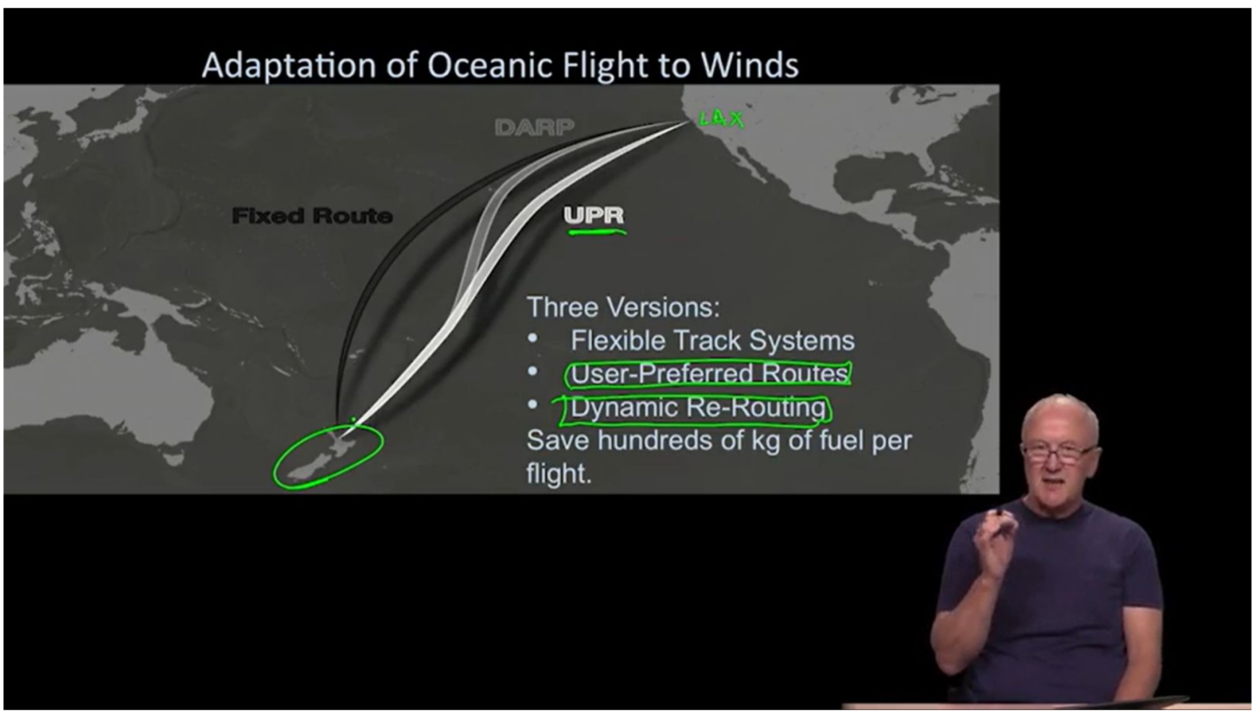

Tailored Arrivals Saved 730 kg Per Flight in
UAL Honolulu to SFO Trials

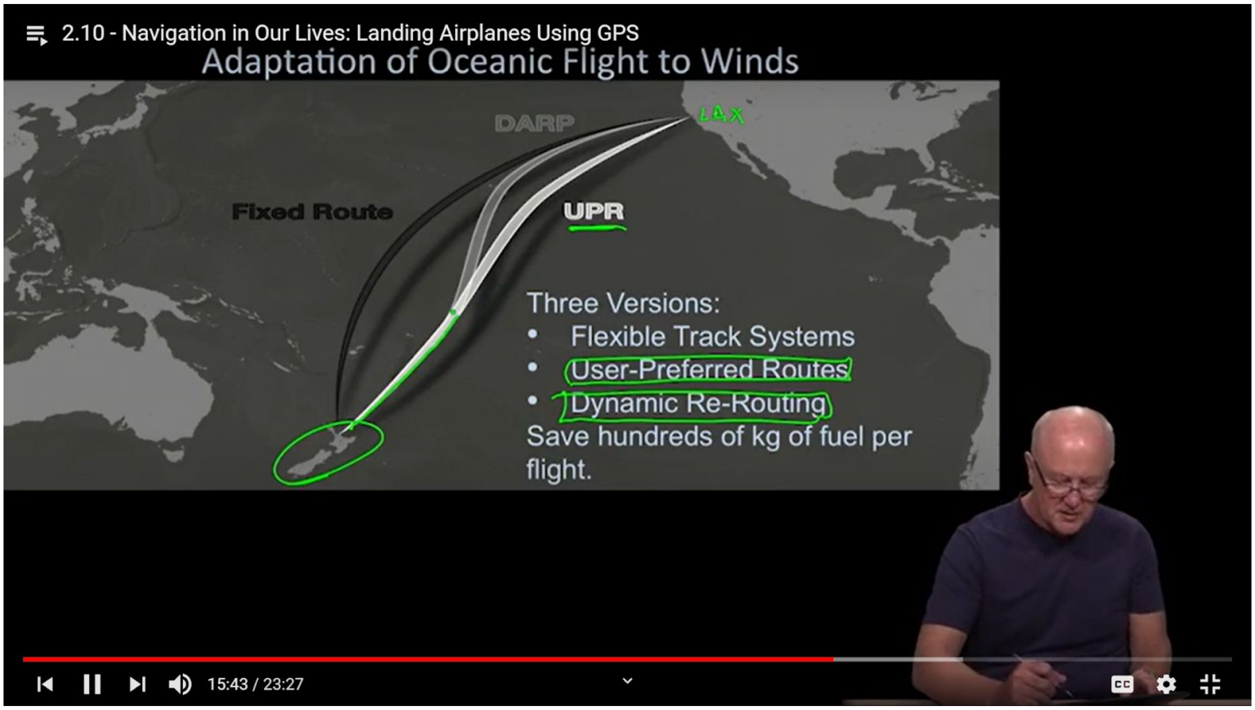

2.10 - Navigation in Our Lives: Landing Airplanes Using GPS
Tailored Arrivals Saved 730 kg Per Flight in
UAL Honolulu to SFO Trials
12:20 / 23:27


Tailored Arrivals Saved 730 kg Per Flight in
UAL Honolulu to SFO Trials

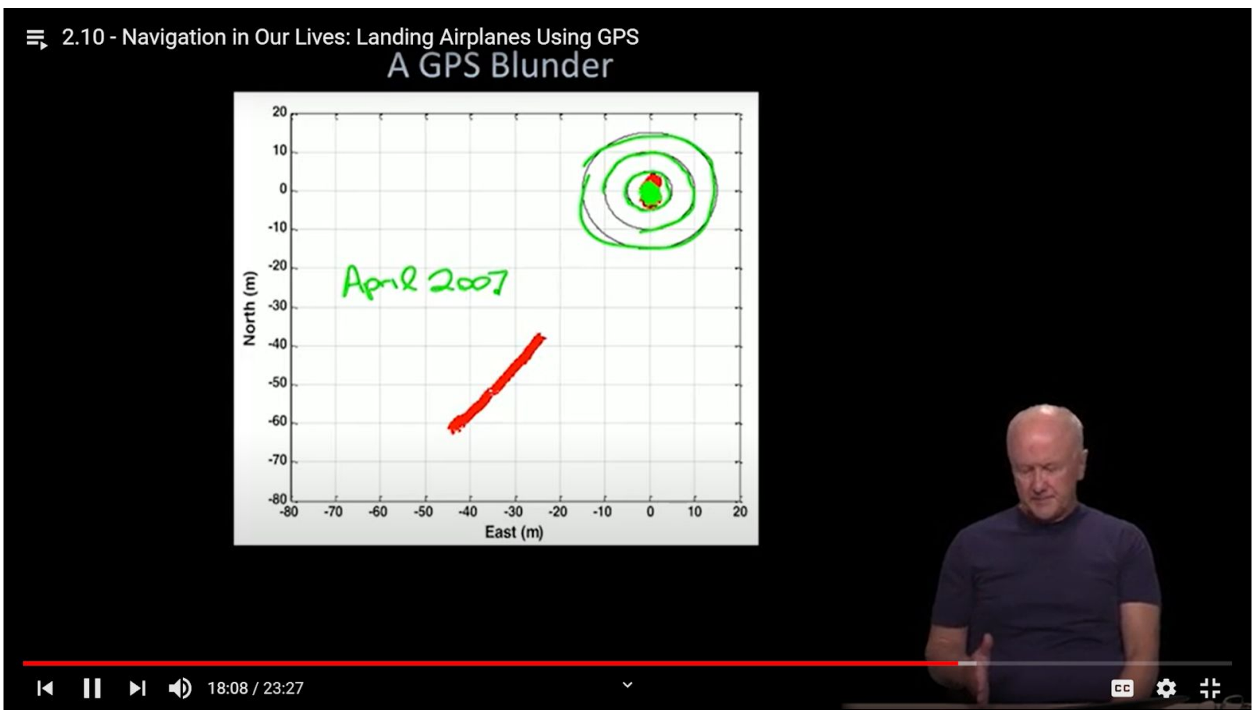

Tailored Arrivals Saved 730 kg Per Flight in
UAL Honolulu to SFO Trials


Adaptation of Oceanic Flight to Winds
DARP
Fixed Route
UPR
Three Versions:
• Flexible Track Systems
• User-Preferred Routes
• Dynamic Re-Routing
Save hundreds of kg of fuel per flight.

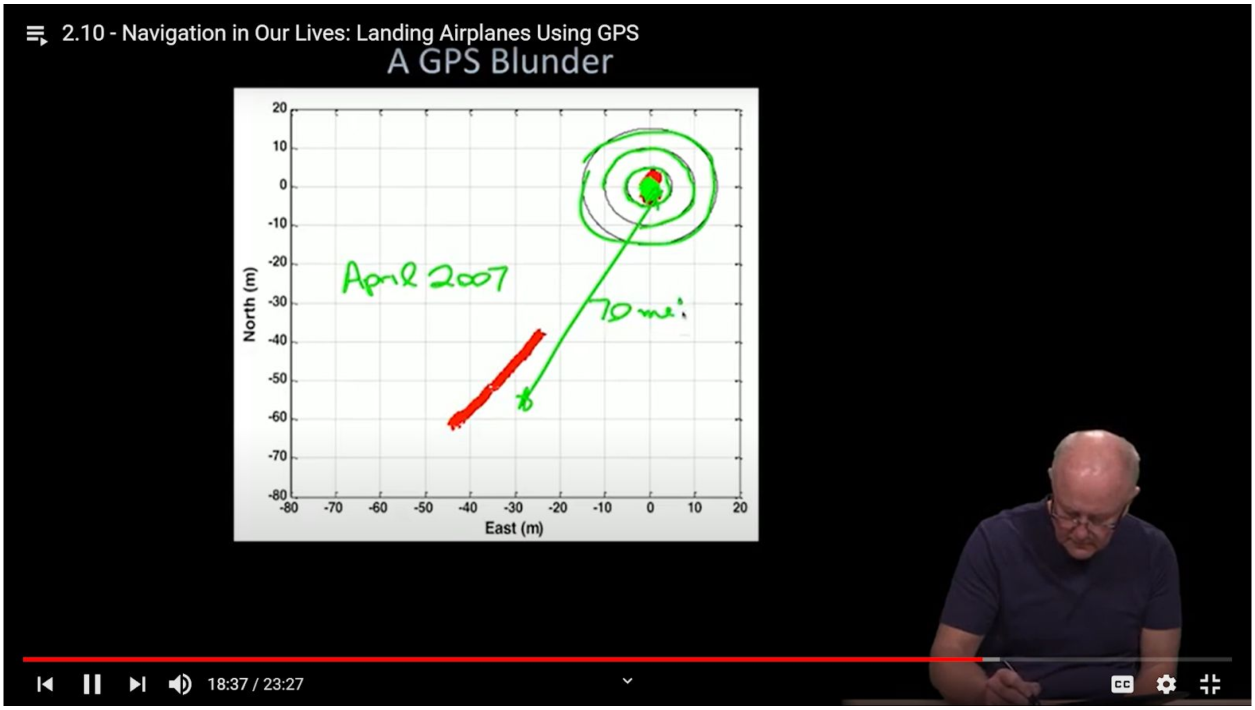

Adaptation of Oceanic Flight to Winds
DARP
LAX
Fixed Route
UPR
Three Versions:
• Flexible Track Systems
• User-Preferred Routes
• Dynamic Re-Routing
Save hundreds of kg of fuel per flight.

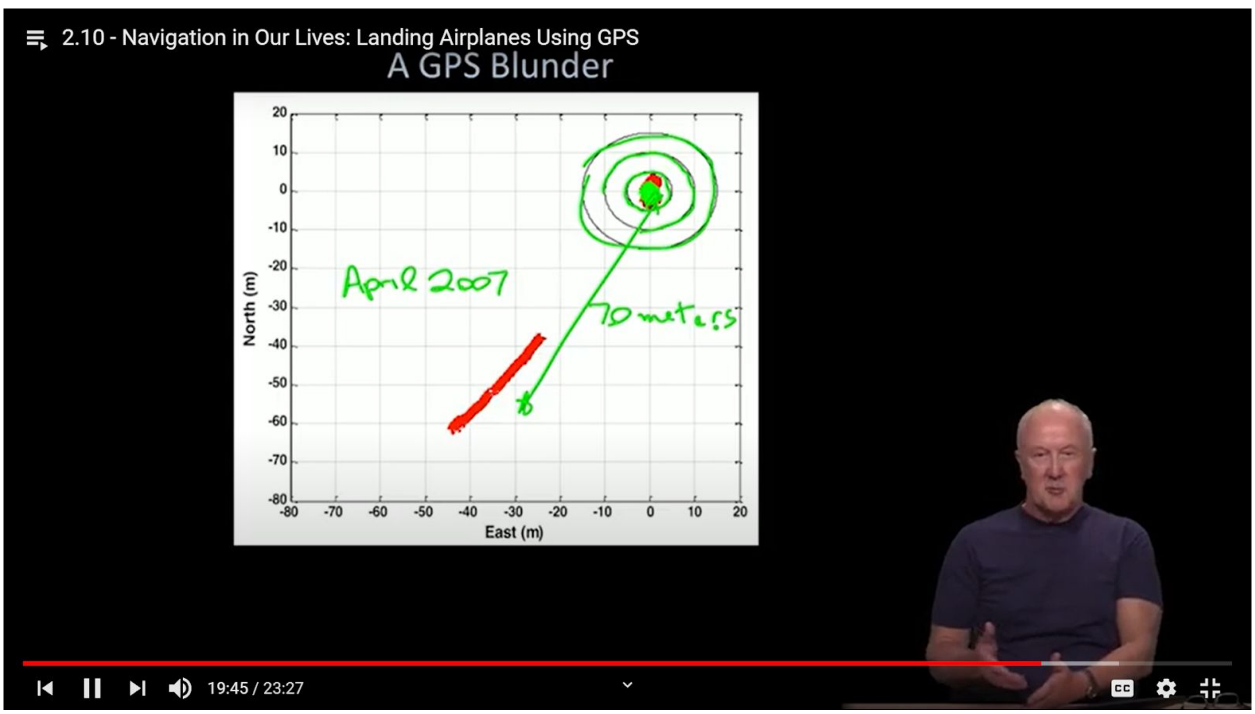


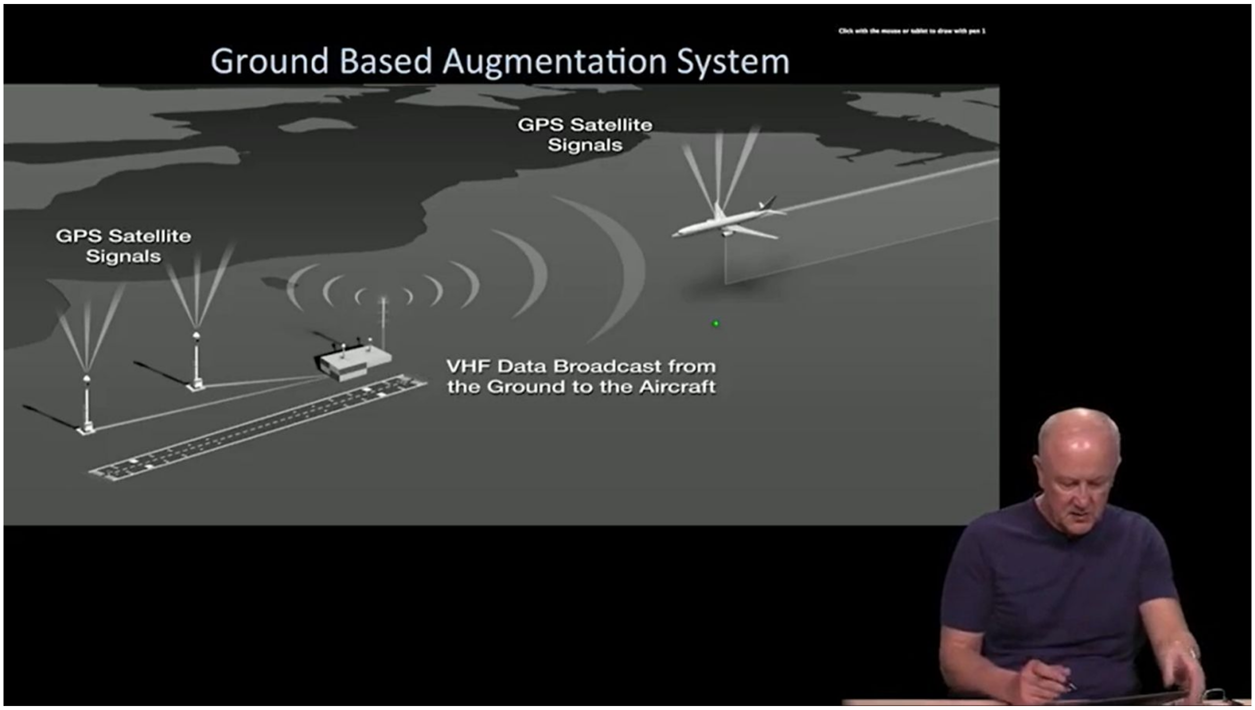
2.10 - Navigation in Our Lives: Landing Airplanes Using GPS
Adaptation of Oceanic Flight to Winds
DARP
LAX
Fixed Route
UPR
Three Versions:
• Flexible Track Systems
• User-Preferred Routes
• Dynamic Re-Routing
Save hundreds of kg of fuel per flight.
15:43 / 23:27

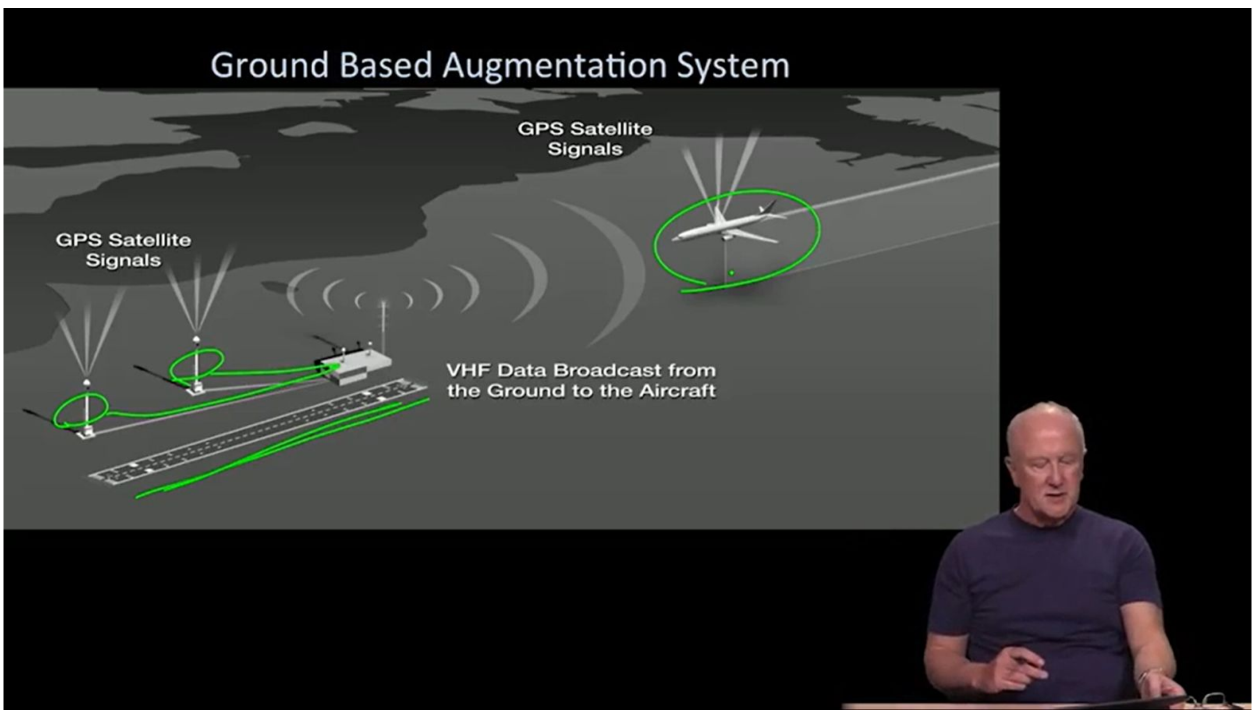


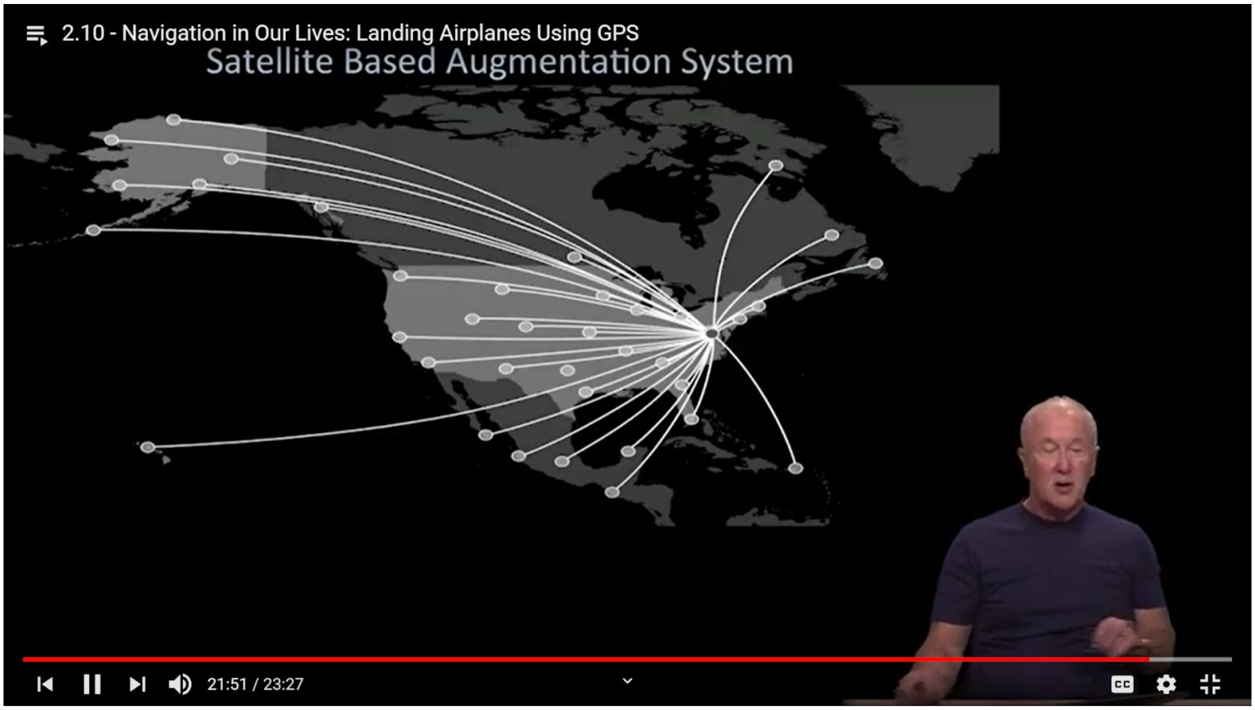
2.10 - Navigation in Our Lives: Landing Airplanes Using GPS
A GPS Blunder
April 2007
North (m)
East (m)
18:08 / 23:27


2.10 - Navigation in Our Lives: Landing Airplanes Using GPS
A GPS Blunder
North (m)
East (m)
April 2007
70 mi
18:37 / 23:27

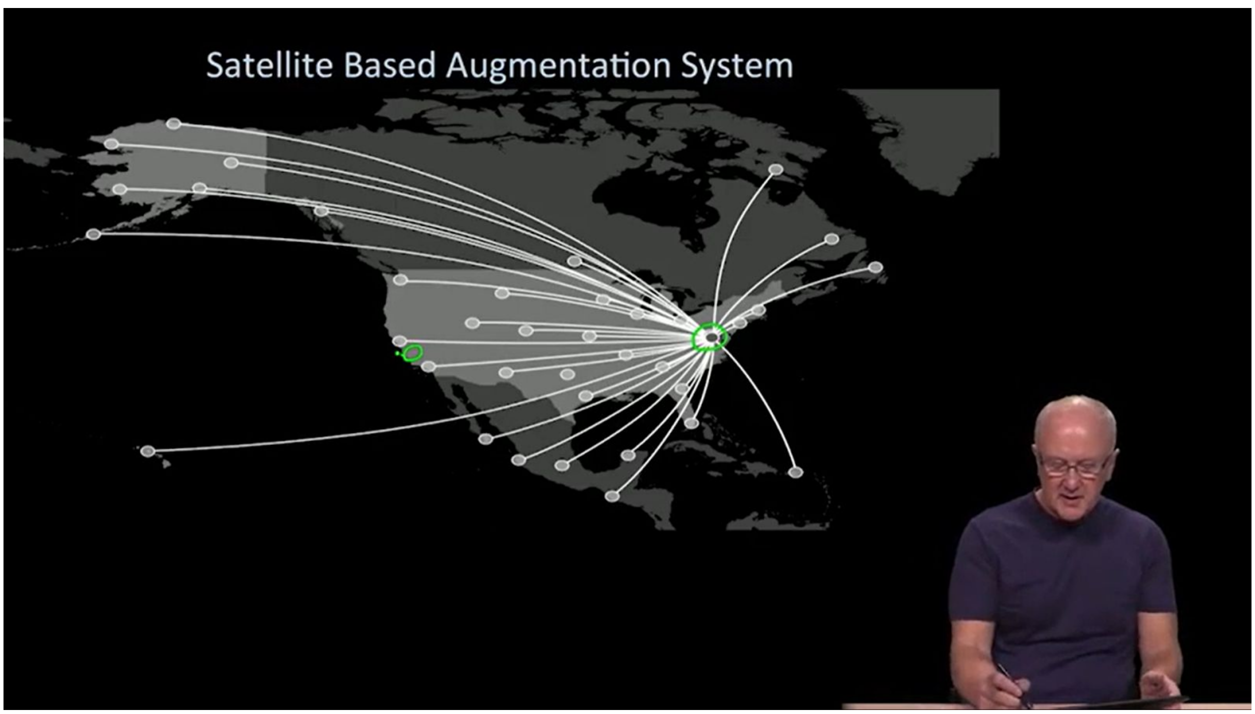

2.10 - Navigation in Our Lives: Landing Airplanes Using GPS
A GPS Blunder
North (m)
East (m)
April 2007
70 meters
19:45 / 23:27


Ground Based Augmentation System
GPS Satellite
Signals
GPS Satellite
Signals
VHF Data Broadcast from
the Ground to the Aircraft

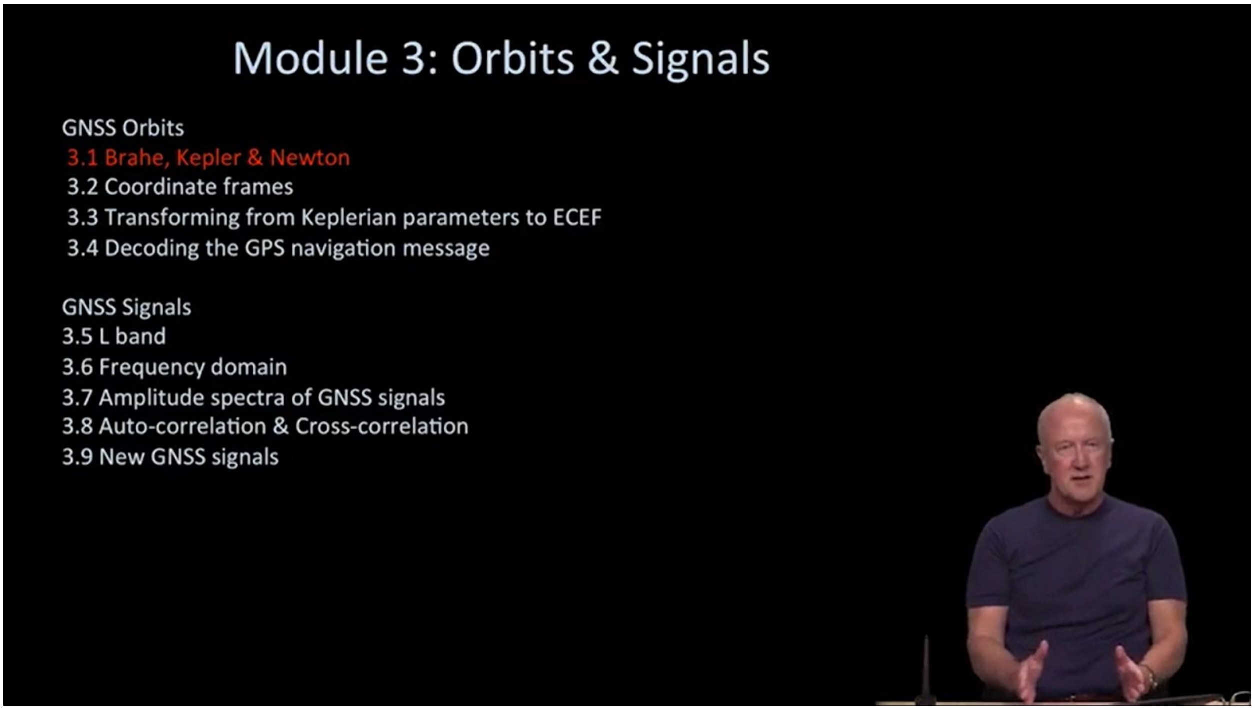

Ground Based Augmentation System
GPS Satellite
Signals
GPS Satellite
Signals
VHF Data Broadcast from
the Ground to the Aircraft



2.10 - Navigation in Our Lives: Landing Airplanes Using GPS
Satellite Based Augmentation System
21:51 / 23:27



Satellite Based Augmentation System


Module 3: Orbits & Signals
GNSS Orbits
3.1 Brahe, Kepler & Newton
3.2 Coordinate frames
3.3 Transforming from Keplerian parameters to ECEF
3.4 Decoding the GPS navigation message
GNSS Signals
3.5 L band
3.6 Frequency domain
3.7 Amplitude spectra of GNSS signals
3.8 Auto-correlation & Cross-correlation
3.9 New GNSS signals