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Satellite Navigation Science and Technology for Africa

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Atmospheric Monitoring and Mitigation

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Atmospheric Mitigation and Monitoring

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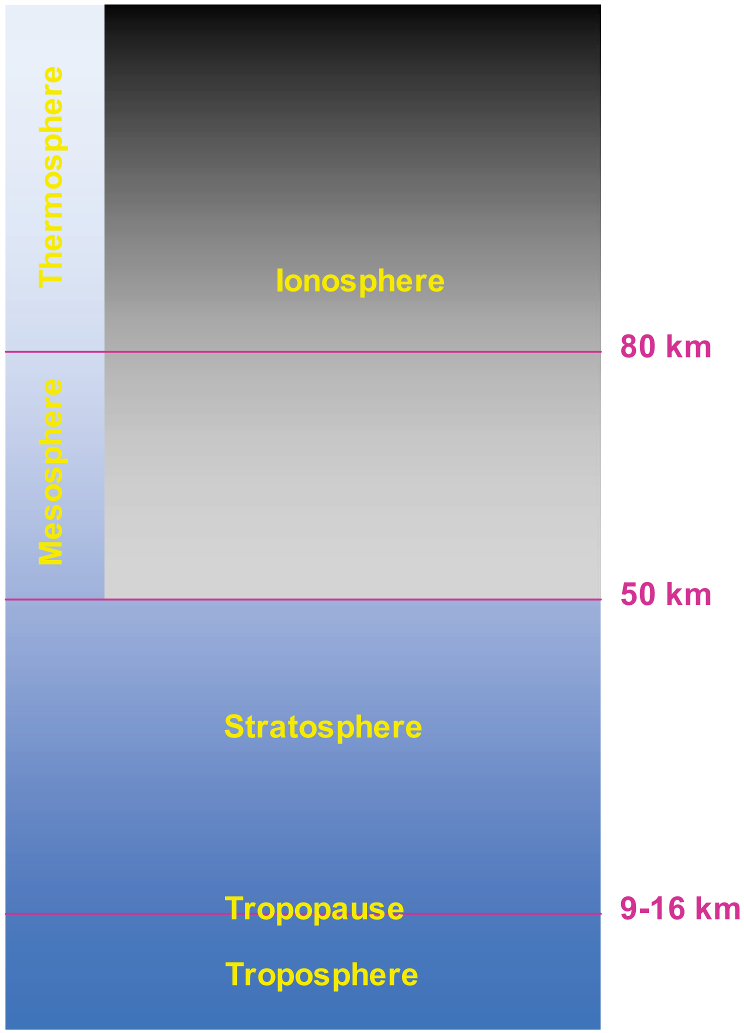
Motivation-1

- GNSS signals travel through the Earth's atmosphere to receivers on or near the ground.
- The signals are refracted, changing their velocity–both speed and direction of travel.
- Measured pseudoranges and carrier phases are biased by metres to 10s of metres.
- Effects can be separated into those due to the electrically neutral atmosphere and those due to the ionosphere.
- In this module, we'll be looking at neutral atmosphere effects.



Motivation-2

- Most of the neutral atmosphere's effect comes from the lowest most part of the atmosphere – the troposphere; hence the effect is often referred to as tropospheric (propagation) delay.
- This delay must be mitigated in some way to improve positioning accuracy.
- On the other hand, GNSS signals contain information about the state of the atmosphere and this can be exploited so that GNSS can also be used as an atmospheric remote sensing monitoring tool for meteorologists ("one persons noise is another person's signal").

Outline

- Motivation
- Maxwell’s Equations
- Refractive Index
- Dispersion
- Polarization
- Ray Equation
- Snell’s Law
- GPS Signals
- Atmospheric Refraction
- Phase and Group Delay
- Atmospheric Profiles and Mapping Functions
- Mitigation Techniques
- GNSS as a Meteorological Sensor

References

Global Positioning System: Signals, Measurements, and Performance by Misra and Enge – Section 4.3, “Signal Propagation Modeling Errors”

“Effect of the Troposphere on GPS Measurements” by F.K. Brunner and W.M. Welsch, *GPS World*, Vol. 4, No. 1, January 1993; pp. 42-51.

“UNB Neutral Atmosphere Models: Development and Performance” by R. Leandro, M. Santos and R.B. Langley, *Proceedings of ION NTM 2006*, Monterey, California, 18-20 January 2006; pp. 564-573.

UNB3m Neutral Atmosphere Delay Model web site <http://gge.unb.ca/Resources/unb3m/unb3m.html>

Maxwell's Equations - 1

Gauss's Law

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

- electric field intensity → $\mathbf{E}$
- electric charge density → ρ
- permittivity of free space aka electric constant $(8.854\ 187\ 817 \times 10^{-12}\ \mathrm{F\ m^{-1}})$ → ε_0

$$\nabla \cdot \mathbf{B} = 0$$

- magnetic induction (magnetic flux density) → $\mathbf{B}$

Faraday's Law

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

Ampere's Law

$$\nabla \times \mathbf{B} - \varepsilon_0 \mu_0 \frac{\partial \mathbf{E}}{\partial t} = \mu_0 \mathbf{J}_m$$

- current density due to charge flow → $\mathbf{J}_m$
- permeability of free space aka magnetic constant $(1.256\ 637\ 061\ 4 \times 10^{-6}\ \mathrm{H\ m^{-1}})$ → μ_0

Maxwell's Equations - 2

For sinusoidal oscillations in free space, Maxwell's equations reduce to:

$$\nabla \cdot \mathbf{E} = 0$$

$$\nabla \cdot \mathbf{H} = 0$$

$$\nabla \times \mathbf{E} + i\omega\mu_0 \mathbf{H} = 0$$

$$\nabla \times \mathbf{H} - i\omega\varepsilon_0 \mathbf{E} = 0$$

magnetic field $\mathbf{H} = \frac{\mathbf{B}}{\mu_0}$

which have the solution

$$\nabla^2 \mathbf{E} + \varepsilon_0 \mu_0 \omega^2 \mathbf{E} = 0$$

$$\nabla^2 \mathbf{H} + \varepsilon_0 \mu_0 \omega^2 \mathbf{H} = 0$$

These equations describe an unattenuated wave propagating with speed

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

A Note on Convention

- In this lecture, we use the physicist's notation of

$$\mathrm{i} = \sqrt{-1}$$

rather than than the electrical engineer's

$$\mathrm{j} = \sqrt{-1}$$

Refractive Index

- **The speed of electromagnetic (EM) waves at some point (x,y,z) in a medium whose permittivity and permiability are ε and μ is given by:**

$$v(x,y,z) = \frac{1}{\sqrt{\varepsilon(x,y,z)\mu(x,y,z)}}$$

- **Refractive index, n, is defined as:**

$$n(x,y,z) = \frac{c}{v(x,y,z)}$$

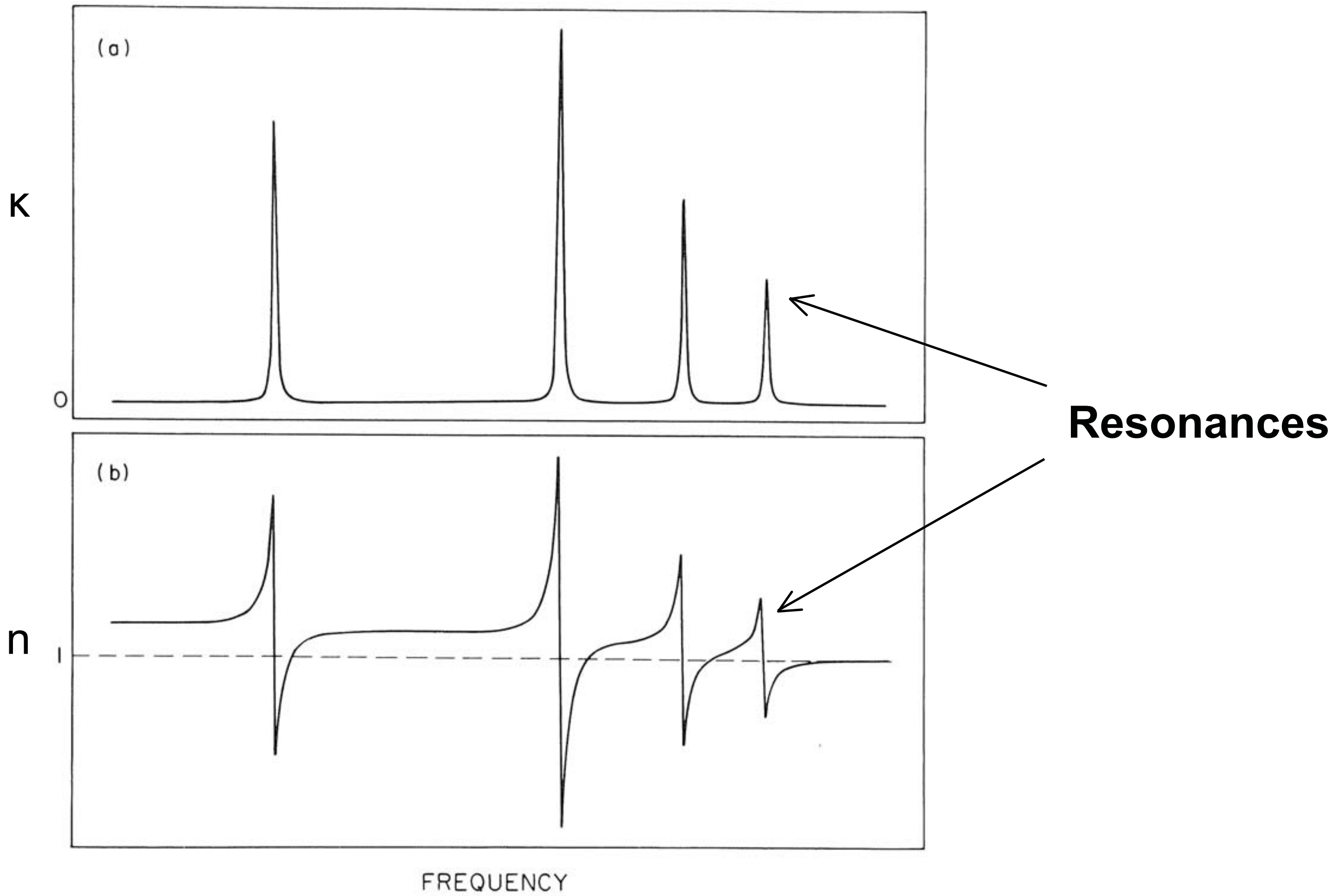
Complex Refractive Index

- In real materials, the polarization does not respond instantaneously to an applied field.
- Resulting dielectric loss can be expressed by a permittivity that is both complex and frequency dependent.
- Real materials also have non-zero direct current conductivity.
- These properties are reflected in the complex refractive index:

$$\tilde{n} = n + i\kappa$$

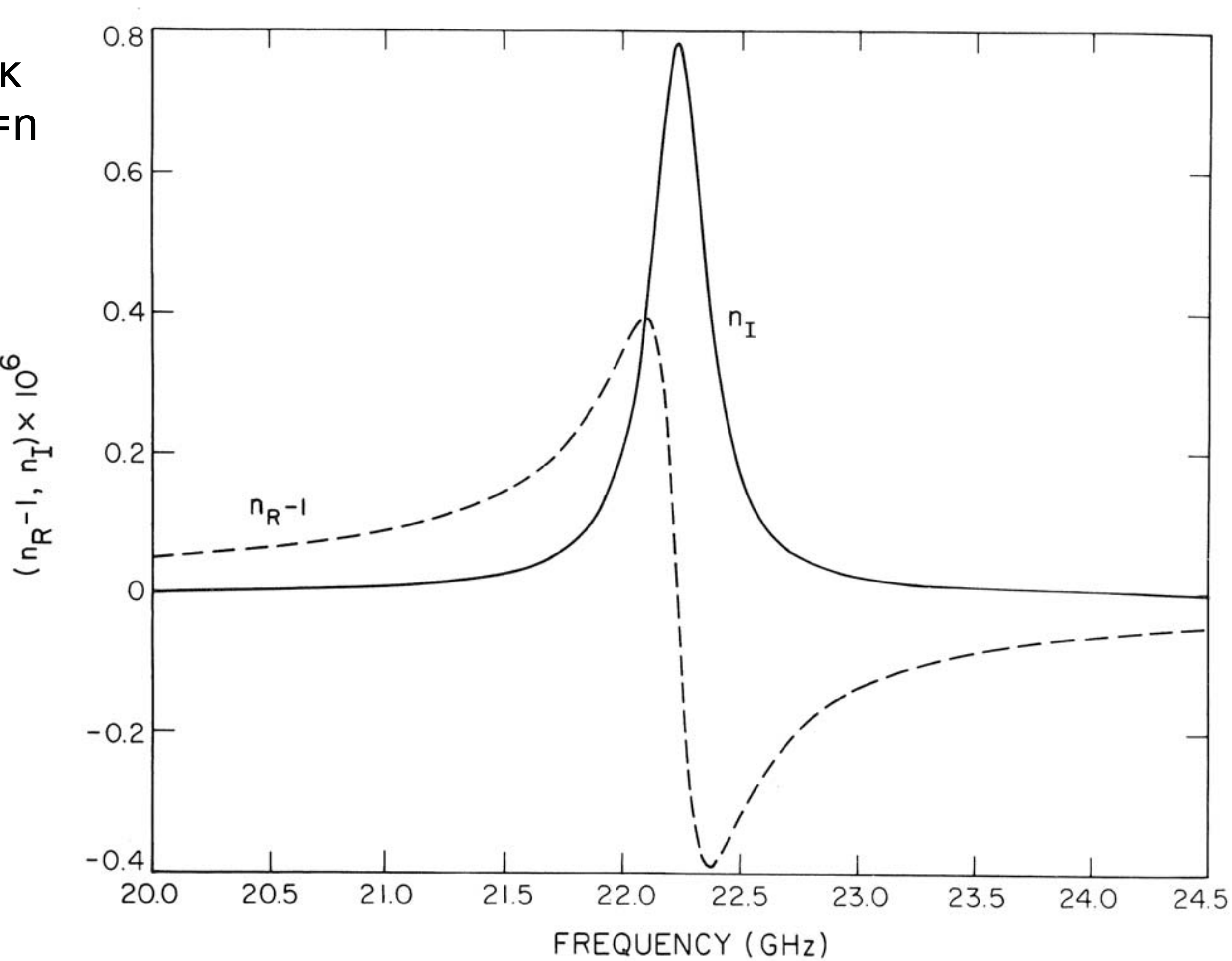
n **is the phase refractive index**
κ **is the extinction (absorption) coefficient.**

Imaginary and Real Parts of Index of Refraction of a Gas



Water Vapour Resonance

$n_I = \kappa$
$n_R = n$



Frequency, Wavelength, Wave Number, and Speed of Light

- **Frequency** f**, angular frequency** ω**, wavelength** λ**, wave number** k**, and the speed of light in a medium** v **are related as follows:**

$$f\lambda = \frac{\omega}{2\pi}\lambda = \frac{\omega}{k} = v$$

- **In a vacuum, we have**

$$f\lambda_0 = \frac{\omega}{2\pi}\lambda_0 = \frac{\omega}{k_0} = c$$

Dispersive Media

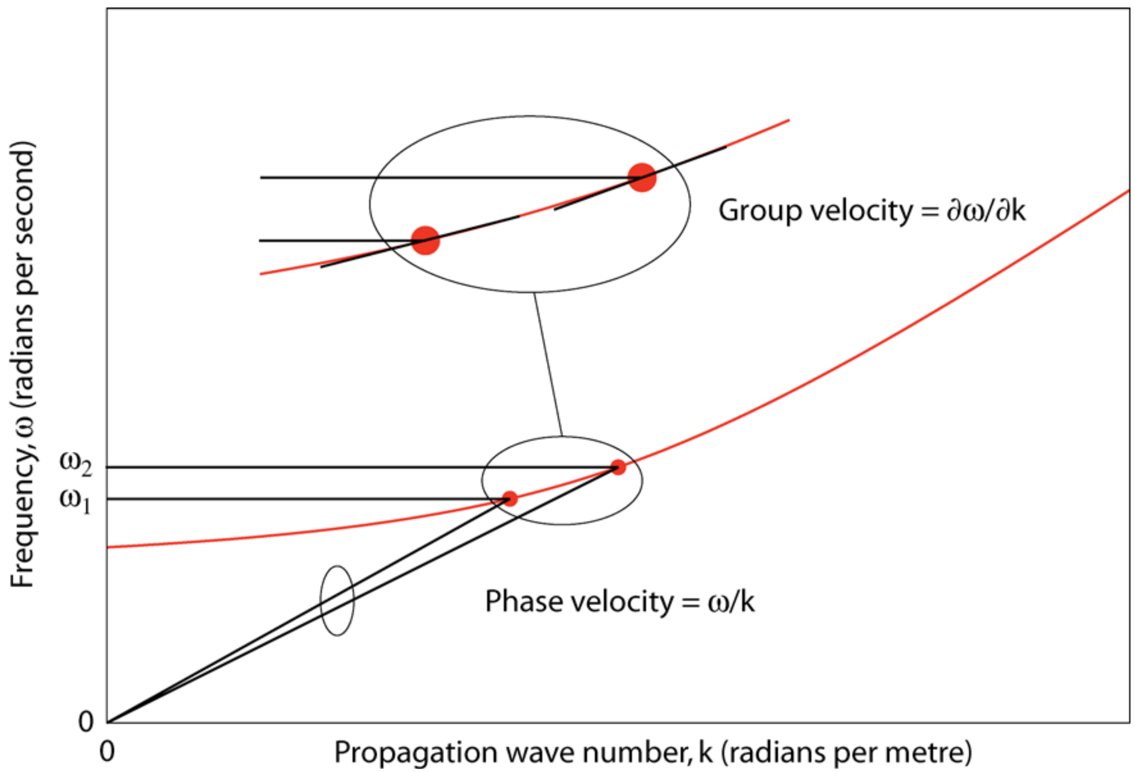
- **In a dispersive medium, the medium's refractive index is a function of frequency and hence the speed of propagation and the wave number are functions of the EM wave's frequency:**

$$v = f(\omega)$$

$$k = f'(\omega)$$

Dispersion Curve

- **A plot of ω vs. k is called a dispersion curve.**



Group Speed

- **In a dispersive medium, waves of different frequencies travel at different speeds. For a modulated signal, the modulation travels at a different speed, the group speed, than the carrier, the phase speed:**

$$v_g = \frac{\partial \omega}{\partial k}$$

$$= v + k \frac{\partial v}{\partial k}$$

Group Refractive Index

- **Associated with the group speed is the group refractive index:**

$$n_g = \frac{c}{v_g}$$

$$= n + \omega \frac{\partial n}{\partial \omega}$$

$$= n + f \frac{\partial n}{\partial f}$$

Solutions to the Wave Equations - 1

- **Various solutions to the electromagnetic (EM) wave equations are possible including the following:**
- **Plane wave moving in the direction k (where $\mathbf{k} = \mathrm{k}\,\hat{\mathrm{s}}$ is the wave vector – don't confuse with the unit vector in the z-direction):**

$$\mathbf{E} = \mathbf{E}_0 e^{-i(\omega t - \mathbf{k} \cdot \mathbf{r})}$$

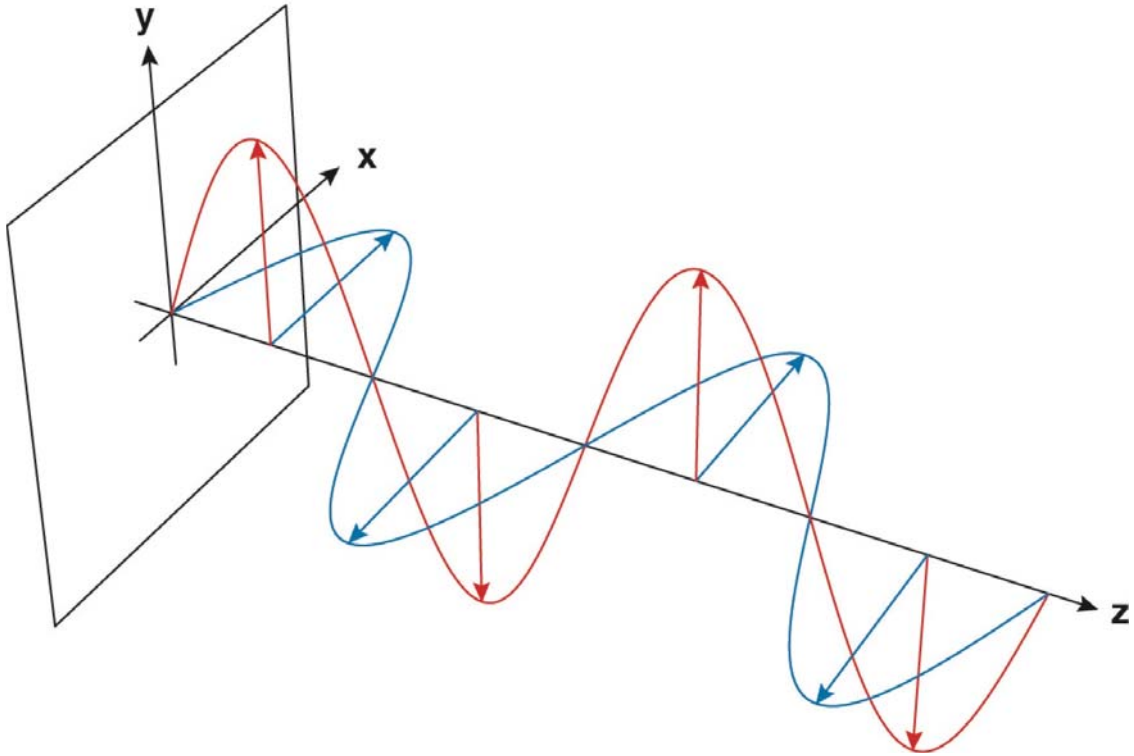
with a corresponding magnetic field solution.

- **Spherical waves emerging from $\mathbf{r} = \mathbf{0}$:**

$$\mathbf{E} = \mathbf{E}_0 e^{-i(\omega t - k r)}$$

Solutions to the Wave Equations - 2

- **Here we have a plane wave travelling in the** z**-direction:**



Polarization

- $\mathbf{E}_0$ **specifies the intensity and polarization of the wave.**
- **Vector describing the electric field can be decomposed into two orthogonal vectors, one parallel to the positive x-axis and one parallel to the positive y-axis.**
- **If x- and y-components have the same phase (or differ by an integer multiple of π), the wave is said to be *linearly* polarized; e.g., the electric field could be oriented either horizontally or vertically.**

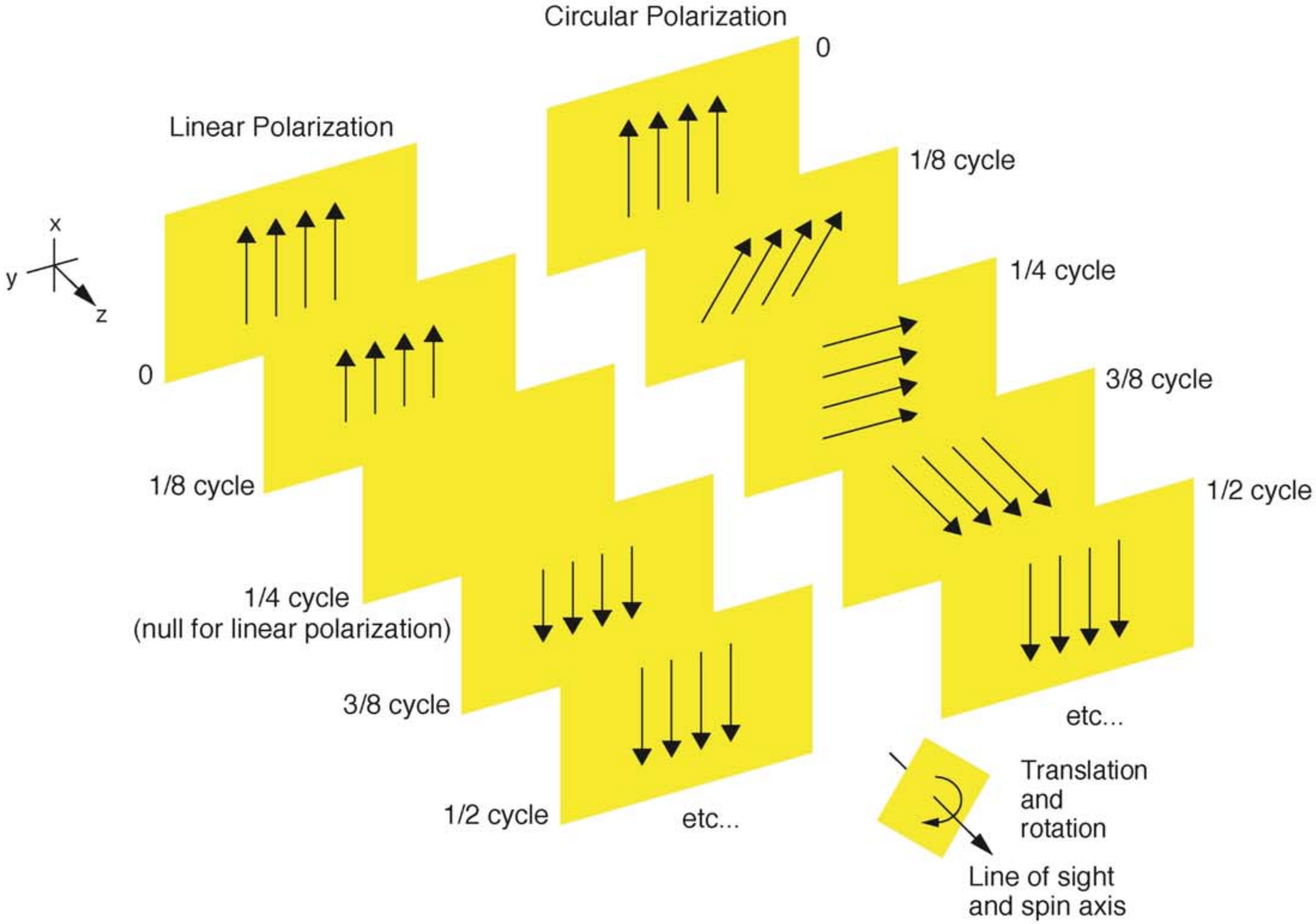
Circular Polarization

- **If the two components differ in phase, their sum describes an ellipse about the z-axis. This is an *elliptically polarized* wave.**
- **If the two components have the same amplitude but are $\pi/2$ (or odd multiple of $\pi/2$) out of phase, the ellipse becomes a circle and the wave is said to be *circularly polarized*.**
- **If, at a fixed point, the electric (and magnetic) field vectors rotate clockwise (counter-clockwise) for an observer looking from the source toward the wave propagation direction, the polarization is *right-handed* (*left-handed*).**

Right-hand Circular Polarization - 1

- **If an antenna with the same polarization sense intercepts circularly polarized waves, the waves induce a constant signal level in the antenna even if the antenna is rotating.**
- **On the other hand, if a linearly polarized antenna intercepts a linearly polarized wave, the electric field's effective amplitude is proportional to** $\cos(\alpha)$ **where** α **is the angle between the field polarization and antenna directions.**
- **GPS EM waves are right-hand circularly polarized.**

Right-hand Circular Polarization - 2



Poynting Vector

- **Specifies the magnitude and direction of energy transport in electromagnetic fields. At a particular point in space, it is given by the cross (vector) product of the electric field and the magnetic field:**

$$\mathbf{s} = \mathbf{E} \times \mathbf{H}$$

- **Note that $\mathbf{s}$ coincides with the direction of propagation of an EM wave.**

The Eikonal Equation - 1

- **This equation is the link between physical (wave) optics and geometric (ray) optics.**
- **A component of the electric field may be written as**

$$E(x,y,z,t) = A(x,y,z)e^{-i[\omega t - k_0 S(x,y,z)]}$$

where A **is the wave amplitude and** S **is called the *eikonal* (from Greek for image).**

- **Constant values of** S **form a family of wavefronts.**

The Eikonal Equation - 2

- **Substituting that equation into the wave equation and assuming a slowly varying medium, we get the *eikonal equation*:**

$$\left|\nabla S\right|^2 = \left(\frac{\partial S}{\partial x}\right)^2 + \left(\frac{\partial S}{\partial y}\right)^2 + \left(\frac{\partial S}{\partial z}\right)^2 = n^2(x, y, z)$$

- **This equation states that the magnitude of the gradient of the wavefront is the square of the index of refraction.**

The Ray Equation - 1

- **Letting r** = (x,y,z) **and taking ŝ**(**r**) **to be the perpendicular to a wavefront, we have**

$$\nabla S = n(\mathbf{r})\hat{s}(\mathbf{r})$$

- **Continuous curves, parallel to ŝ**(**r**)**, are called *rays*.**
- **Taking the gradient of the eikonal equation (with** ds **an increment along a ray), we get the *ray equation*:**

$$\frac{d}{ds}\left(n\,\hat{\mathbf{s}}\right) = \nabla n$$

The Ray Equation - 2

- The ray equation may be solved to find the trajectory of a ray given n(**r**). For example, let's say that n varies only in the y direction and the ray lies initially in the xy plane making an angle θ_0 with the y axis. So, with

$$\hat{\mathbf{s}} = \mathbf{i}\alpha + \mathbf{j}\beta + \mathbf{k}\gamma$$

$$= \mathbf{i}\sin\theta + \mathbf{j}\cos\theta + \mathbf{k}\gamma$$

we have

$$\frac{d}{ds}\left(n\sin\theta\right) = 0 \quad \frac{d}{ds}\left(n\cos\theta\right) = \frac{dn}{dy} \quad \frac{d}{ds}\left(n\gamma\right) = 0$$

The Ray Equation - 3

- **And since**

$$\hat{\mathbf{s}}_0 = \mathbf{i}\sin\theta_0 + \mathbf{j}\cos\theta_0$$

we have

$$n\sin\theta = \text{constant} = n_0 \sin\theta_0$$

$$n\,\gamma = \text{constant} = 0$$

- **The first equation is simply *Snell's Law* and the second equation tells us the ray remains in the** xy **plane.**

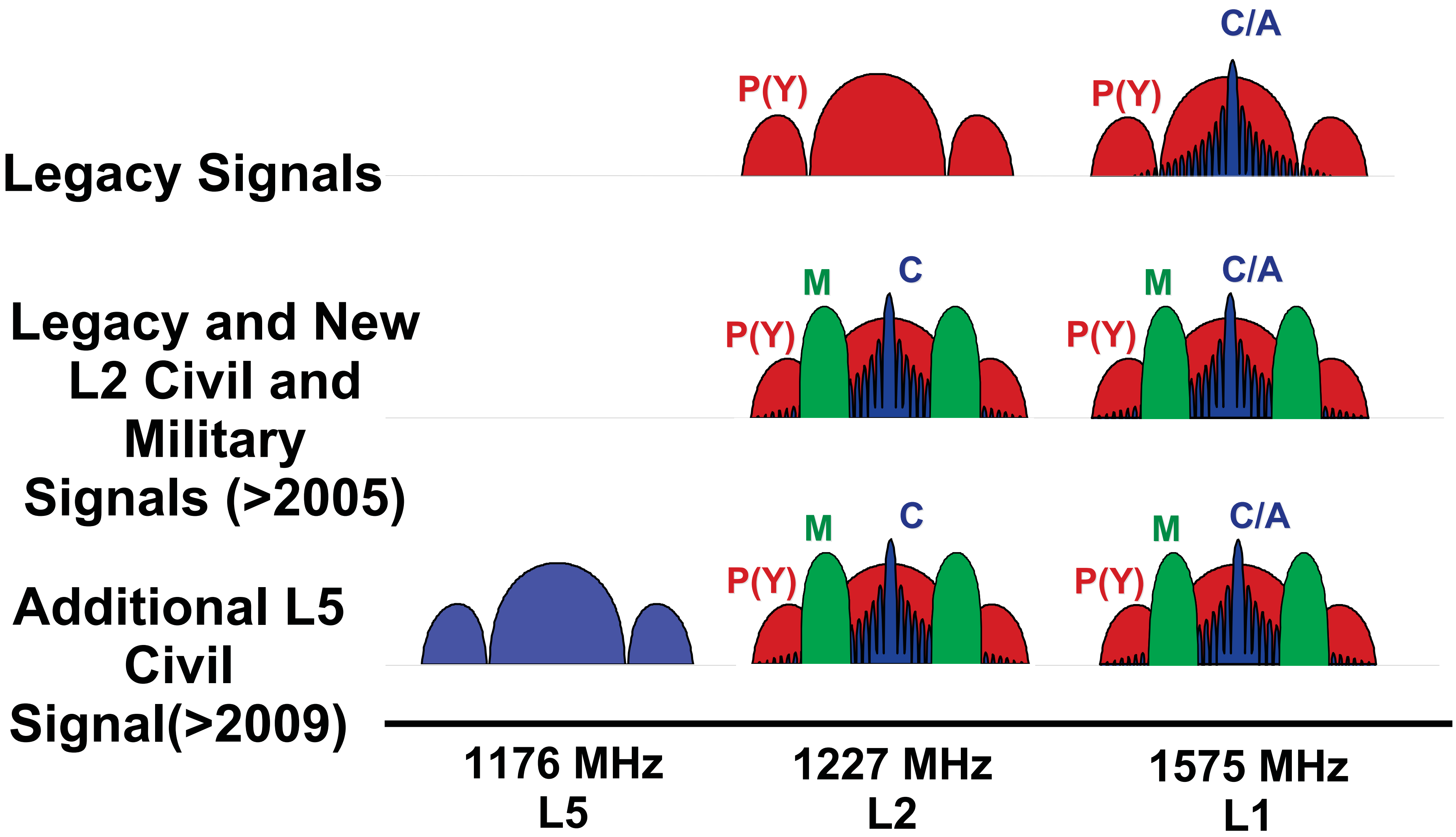
Snell's Law for Spherically Symmetric Atmosphere

- **Snell's Law is slightly more complicated for a medium in which** n **varies radially:**

$$n\,r\sin\theta = n_0\,r_0\sin\theta_0$$

where r **is the radial coordinate.**

GPS Signal Modernization



GPS Observation Equations

Pseudorange:

$$P(t) = \rho(t) + c[dt_r(t) - dt^s(t-\tau)] + I(t) + T(t) + \varepsilon_P(t)$$

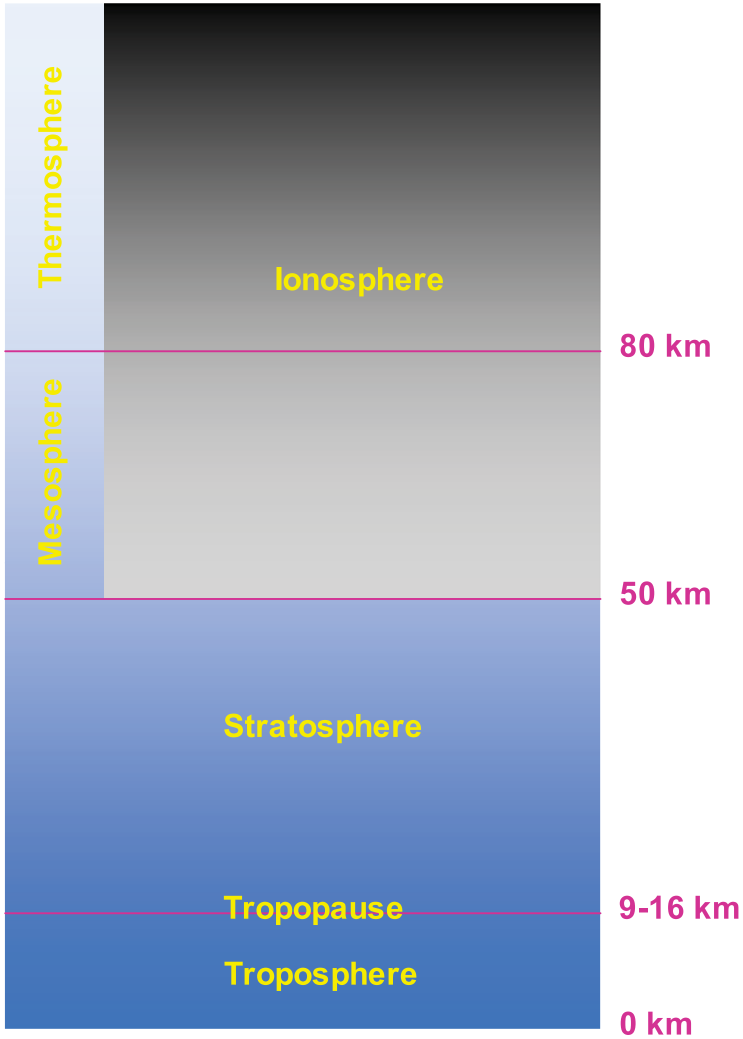
Carrier phase:

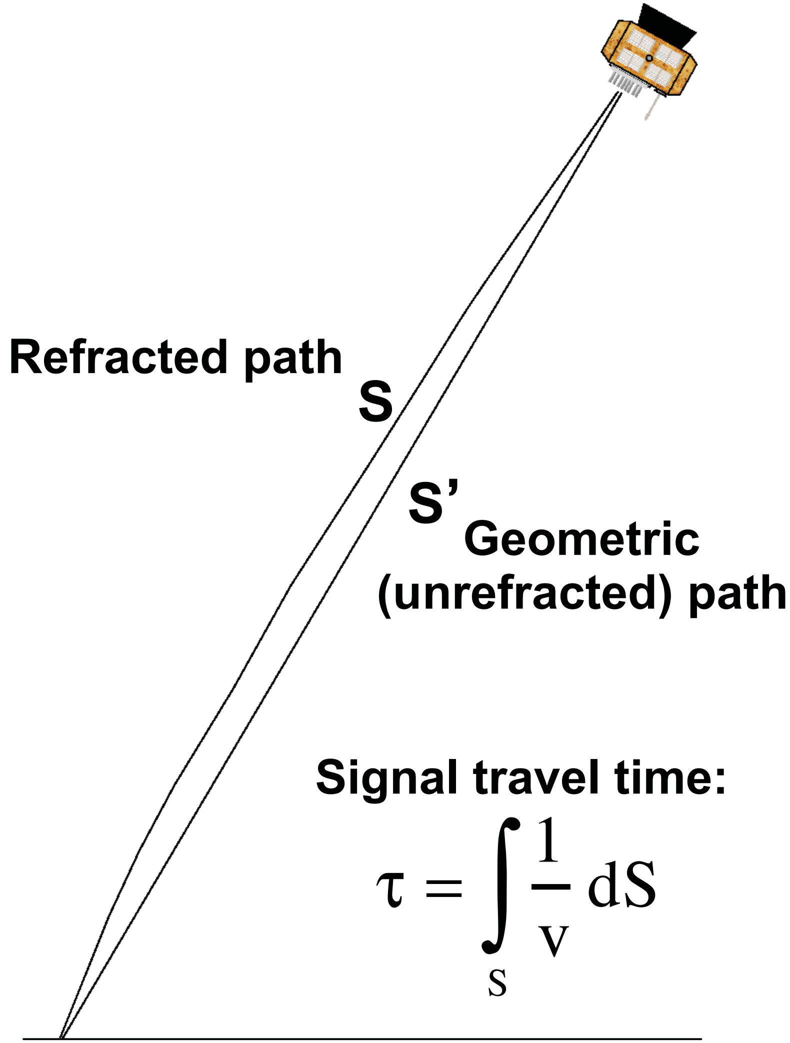
$$\Phi(t) = \lambda\,\phi(t)$$
$$= \rho(t) + c[dt_r(t) - dt^s(t-\tau)] - I(t) + T(t) + \lambda N + \varepsilon_\Phi(t)$$

t	- signal reception time
λ	- wavelength
c	- speed of light
ρ	- geometric range
τ	- signal transit time
dt_r	- receiver clock offset

dt^s	- satellite clock offset
I	- ionospheric delay
T	- tropospheric delay
N	- integer ambiguity
ε_P	- pseudorange noise
ε_Φ	- carrier phase noise

Atmospheric Refraction





Signal travel time:

$$\tau = \int_S \frac{1}{v} \, dS$$

Refractive Index of Air

- At radio frequencies, imaginary part of refractive index of air is negligible except near the 22.235 GHz water vapour and 60 GHz oxygen lines
- And air is essentially a non-dispersive medium, with n independent of frequency.
- Refractive index of parcel of moist air is a function of its temperature, partial pressure of dry constituents (nitrogen, oxygen, etc.) and partial pressure of water vapour:

$n = n(T, P_d, e)$

Refractivity

- At sea level, values of the refractive index of air are close to 1.0003, becoming smaller with increasing height
- A more useful quantity is refractivity, N:

$$N = 10^6 (n - 1)$$

with sea level values near 300

Refractivity Expressions and Constants

Ignoring so-called compressibility factors (they account for non-ideal behaviour of gases with values near unity), we have:

$$N = K_1 \frac{P_d}{T} + K_2 \frac{e}{T} + K_3 \frac{e}{T^2}$$

Dry ***Wet***

Original formulation due to Smith and Weintraub, 1953

or

$$N = K_1 \frac{M}{M_d} \frac{P}{T} + \left(K_2 - K_1 \frac{M}{M_d} \right) \frac{e}{T} + K_3 \frac{e}{T^2}$$

Hydrostatic ***Non-hydrostatic or "Wet"***

Revised formulation due to Davis et al., 1985

How We Compute N: Modern Hydrostatic/Non-hydrostatic Convention

$$N = K_1 R_d \rho + \left(K_2 - K_1 \frac{M_w}{M_d} \right) \frac{e}{T} + K_3 \frac{e}{T^2}$$

$$= K_1 R_d \rho + \left(K_2 - K_1 \frac{R_d}{R_w} \right) \frac{e}{T} + K_3 \frac{e}{T^2}$$

$$= K_1 R_d \rho + K_2' \frac{e}{T} + K_3 \frac{e}{T^2}$$

$$= K_1 R_d \left(\frac{P - e}{R_d T} + \frac{e}{R_w T} \right) + K_2' \frac{e}{T} + K_3 \frac{e}{T^2}$$

Definitions

P = total (barometric) pressure in millibars (mbar) = hectopascals (hPa)

P_d = partial pressure of dry constituents (mbar)

e = partial pressure of water vapour (mbar); can be determined from relative humidity and vice versa

T = temperature in kelvins (K)

M = molar mass of moist air

M_d = molar mass of dry air

M_w = molar mass of water vapour

ρ = density of moist air

R_d = gas constant for dry air

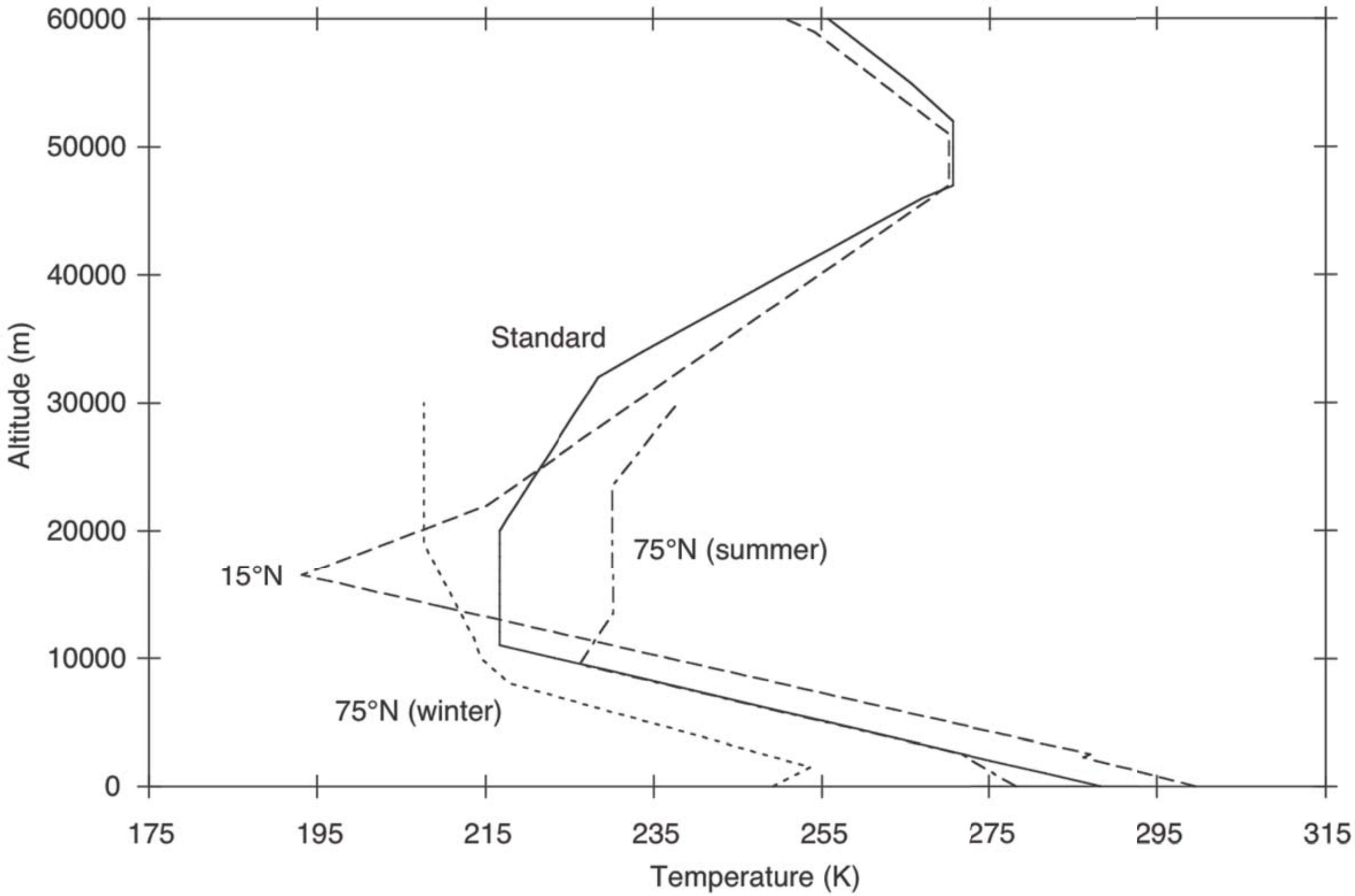
R_w = gas constant for water vapour

K_1, K_2, K_2', K_3 = refractivity constants

Atmospheric Profiles

- Barometric pressure, temperature, and water vapour pressure (relative humidity) vary with height above the Earth's surface.
- Barometric pressure decreases more or less exponentially with increasing height.
- Temperature and water vapour profiles are more variable.

Standard Atmospheres

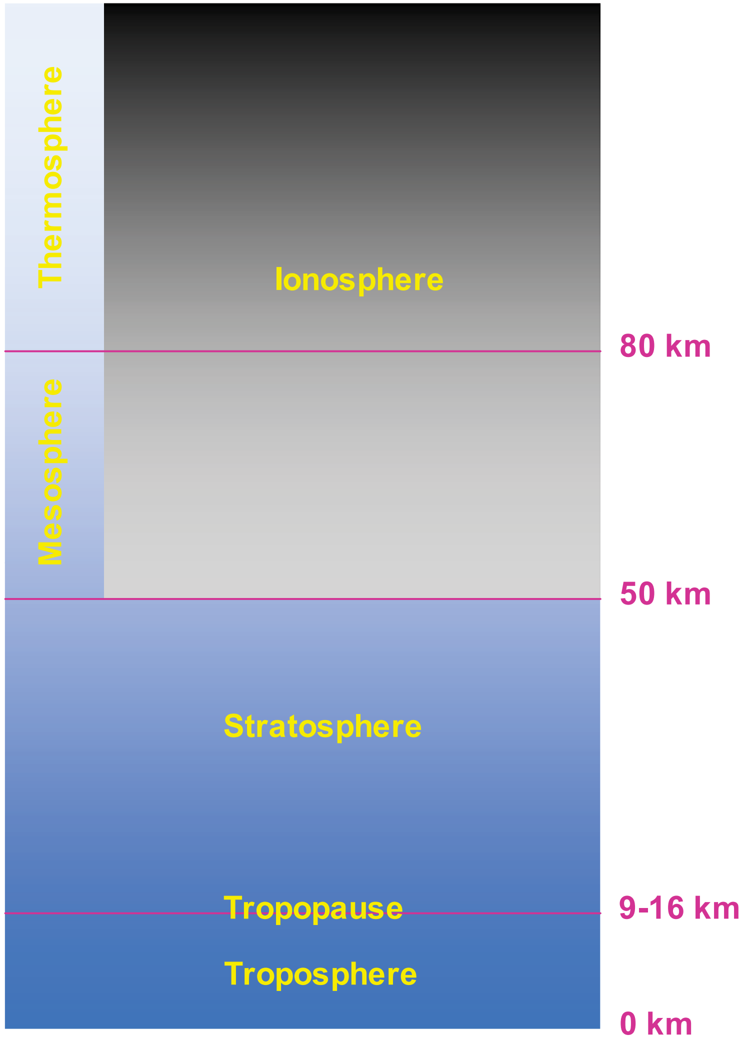


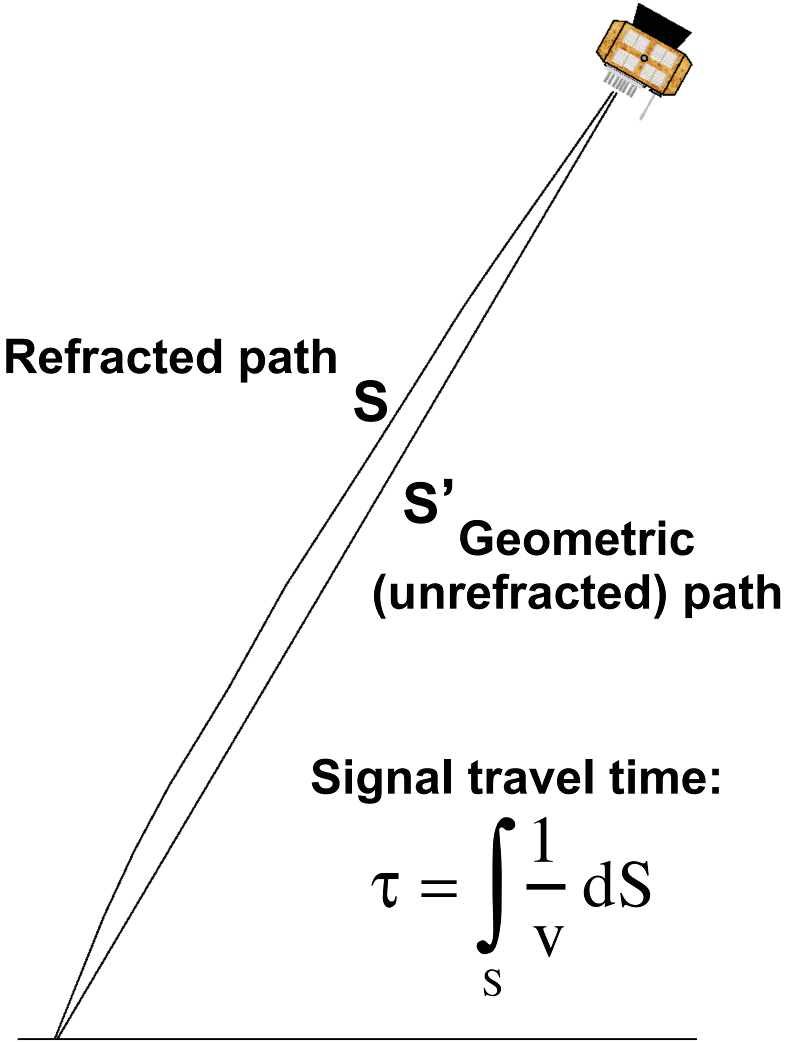
Effect of the Neutral Atmosphere on GNSS

- We turn now to consider the effect of the neutral atmosphere refraction on GNSS measurements.

- GNSS measurements are affected by the integrated effects of refractivity all along the signal raypath.

Atmospheric Refraction





Signal travel time:

$$\tau = \int_S \frac{1}{v} dS$$

Phase and Group Delay-1

$$\Delta\tau = \int_S \frac{1}{v}\, dS - \int_{S'} \frac{1}{c}\, dS'$$

$$d\Phi = c\,\Delta\tau$$

$$= \int_S n\, dS - \int_{S'} dS'$$

$$= \int_S (n-1)\, dS + \left[\int_S dS - \int_{S'} dS' \right]$$

Effect of raypath bending

$$dP = \int_S (n_g - 1)\, dS + \left[\int_S dS - \int_{S'} dS' \right]$$

Phase and Group Delay-2

- Remember: the neutral atmosphere is non-dispersive for radio waves up to a frequency of about 20 GHz.

- So, $n_g = n$ and $d\Phi = dP$.

- For a particular satellite at a particular epoch, the neutral atmosphere delay is identical for the pseudorange and carrier phase on all the satellite's frequencies.

Neutral Atmosphere Zenith Delay

- The zenith delay is the total delay experienced by a signal arriving from directly overhead – the zenith direction.

- Typically separated into hydrostatic and non-hydrostatic components:

$$d_h^z = 10^{-6} \int_r N_h dh$$

$$d_{nh}^z = 10^{-6} \int_r N_{nh} dh$$

Tropospheric Slant Propagation Delay

Zenith delay is mapped to the signal slant path at elevation angle θ using a mapping function (also called an obliquity factor):

zenith delays

$$T = d_h^z m_h(\theta) + d_{nh}^z m_{nh}(\theta)$$

mapping functions

Mapping Functions: Continued Fraction Form

$$m(\theta) = \cfrac{1}{\sin\theta + \cfrac{a}{\sin\theta + \cfrac{b}{\sin\theta + \cfrac{c}{\sin\theta + \ldots}}}}$$

Setting a = 0, results in the "flat Earth" approximation (a poor model):

$$m(\theta) = \frac{1}{\sin\theta}$$

“Two Constants” Models

$$m(\theta) = \frac{1}{\sin\theta + \dfrac{a}{\tan\theta + b}}$$

Continued fraction truncated after the “b term” and, in this term, sin(θ) is replaced by tan(θ) to ensure that m(θ) is unity at θ = 90°.

Normalized Continued Fraction Form

$$m(\theta) = \frac{1 + \cfrac{a}{1 + \cfrac{b}{1 + c}}}{\sin\theta + \cfrac{a}{\sin\theta + \cfrac{b}{\sin\theta + c}}}$$

Used by "modern" mapping functions.

Constants determined by ray tracing (to be discussed later) through real or modelled atmospheres.

Profile Models

Profiles ("Dry" and "Wet")

Hopfield (1969)
- Yionoulis (1970)
- Goad & Goodman (1974)
- Black (1978)
- Black & Eisner (1984)

Saastamoinen (1973)
- Standard
- Precise
- Davis et al. (1986)

Profiles ("Wet")

Chao (1972)
Berman 70
Berman 76

Mapping Functions

Marini (1972)
Marini & Murray (1973)
Chao (1972)
Lanyi (1984)
Davis, CfA-2.2 (1986)
Ifadis (1986)
Herring (1992)
UNSW931 (1995)
Niell (1996)
Vienna Mapping Function 1, VMF1 (2006)
Global Mapping Function, GMF (2006)

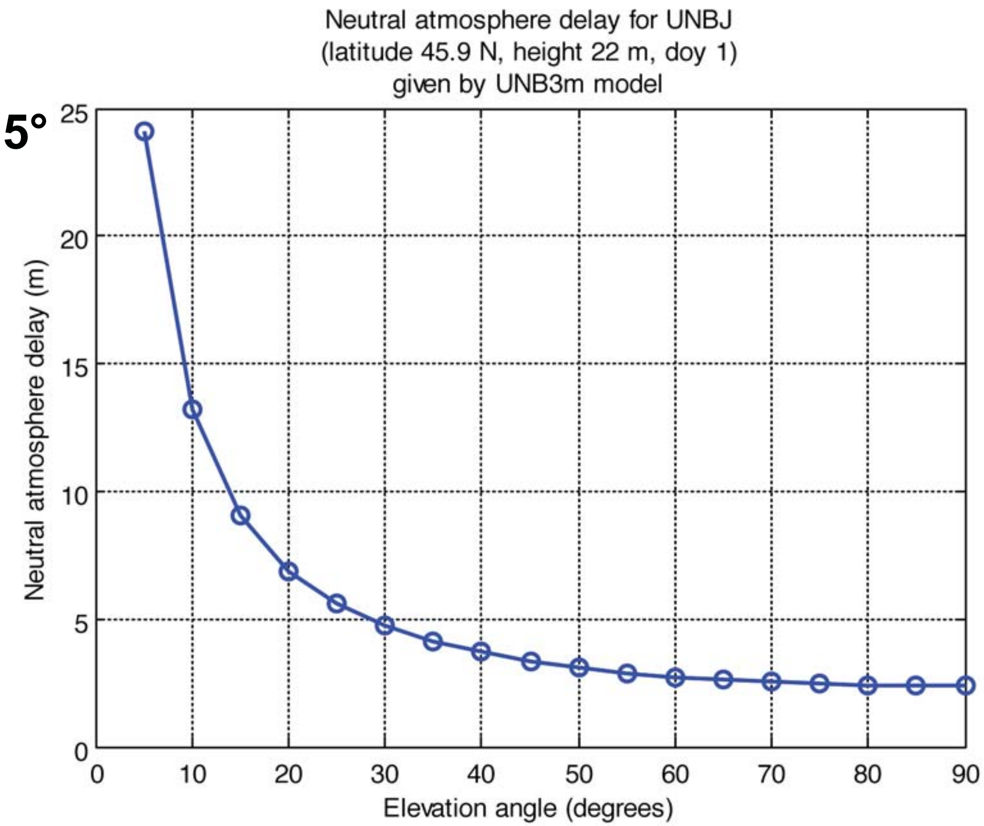
Combined Models (Profile + Mapping Function)

Altshuler & Kalaghan (1974)
NATO (1993)
Original WAAS (1995)

In general, these models do not perform as well as the others previously mentioned,

So, How Much Delay is Imparted by the Neutral Atmosphere?

24.2 m @ 5°



2.4 m @ 90°

Neutral Atmosphere Delay Mitigation Techniques

1. No mitigation technique
2. Discard low-elevation-angle observations
3. Predict neutral atmosphere delay (NAD) using models
4. Reduce NAD using between-receiver single differencing
5. Estimate NAD from GPS observations
6. Measure NAD using external techniques
7. Interpolate NAD from estimates at nearby stations

Neutral Atmosphere Delay Mitigation Techniques

1. **No mitigation technique**
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No Mitigation

- In standalone GNSS positioning, suffer the full effect of the neutral atmosphere propagation delay

- Many metres of horizontal and vertical position error.

Neutral Atmosphere Delay Mitigation Techniques

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Discard Low-Elevation-Angle Observations

- **Reduces the effect of neutral atmosphere delay but position error in standalone positioning can still be at the metre level.**

Neutral Atmosphere Delay Mitigation Techniques

1. No mitigation technique
2. Discard low-elevation-angle observations
3. **Predict neutral atmosphere delay (NAD) using models**
4. Reduce NAD using between-receiver single differencing
5. Estimate NAD from GPS observations
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Predict Neutral Atmosphere Delay (NAD) Using Models

- As we have seen, many profiles and mapping functions have been developed over the years. Let's take a look at one particular set.

UNB Neutral Atmosphere Prediction Models

- A sequence of predictive, climatology-based, hybrid models
- Based on Saastamoinen zenith delays, Niell mapping functions, look-up tables of sea-level pressure, temperature, water vapour pressure or relative humidity, and lapse rate annual means and amplitudes, and height propagators
- UNB3 widely used; basis for SBAS in-receiver model (Niell mapping functions replaced by simpler Black & Eisner model); application details in RTCA Minimum Operational Performance Standards document

UNB Neutral Atmosphere Prediction Model Zenith Delays

$$d_h^z = \frac{10^{-6} K_1 R_d}{g_m} \cdot P_0 \cdot \left(1 - \frac{\beta H}{T_0}\right)^{\frac{g}{R_d \beta}}$$

← **Height propagators**

$$d_{nh}^z = \frac{10^{-6}\left(T_m K_2' + K_3\right) R_d}{g_m \lambda' - \beta R_d} \cdot \frac{e_0}{T_0} \cdot \left(1 - \frac{\beta H}{T_0}\right)^{\frac{\lambda' g}{R_d \beta} - 1}$$

Definitions-1

- d_h^z and d_{nh}^z are the hydrostatic and non-hydrostatic zenith delays (m)
- T_0, P_0, and e_0 are MSL temperature (K), barometric pressure (mbar), and water vapour pressure (mbar) – e_0 can be related to relative humidity
- β and λ are the temperature lapse rate (K m^{-1}) and water vapour pressure height factor (unitless)

Definitons-2

- H is orthometric height of site (m)
- R_d is the gas constant for dry air (287.054 J kg^{-1} K^{-1})
- g_m is acceleration of gravity at atmospheric column centroid (m s^{-2})

$$g_m = 9.784\left(1 - 2.66 \times 10^{-3}\cos(2\phi) - 2.8 \times 10^{-7} H\right)$$

- g is standard acceleration of gravity (9.80665 m s^{-2})

Definitions-3

- **T_m is the mean temperature of water vapour (K)**

$$T_m = \left(T_0 - \beta H\right)\left(1 - \frac{\beta R_d}{g_m \lambda'}\right)$$

- **$\lambda' = \lambda + 1$ (unitless)**
- **$K_1 = 77.60$ K mbar^{-1}**
- **$K_2' = 16.6$ K mbar^{-1}**
- **$K_3 = 377600$ K2 mbar^{-1}**

UNB3

- **UNB3 look-up table has 5 latitude sets of mean (average) and annual MSL values**
- **Values are interpolated for latitude of station**
- **Day-of-year values computed from**

$$X_{\phi,doy} = Avg_{\varphi} - Amp_{\phi} \cdot \cos\left(\left(doy - 28\right)\frac{2\pi}{365.25}\right)$$

- **UNB3 is capable of predicting total zenith delays with average uncertainties of 5 cm under normal atmospheric conditions.**
- **Corresponding SBAS model error is significantly overbounded for safety reasons**

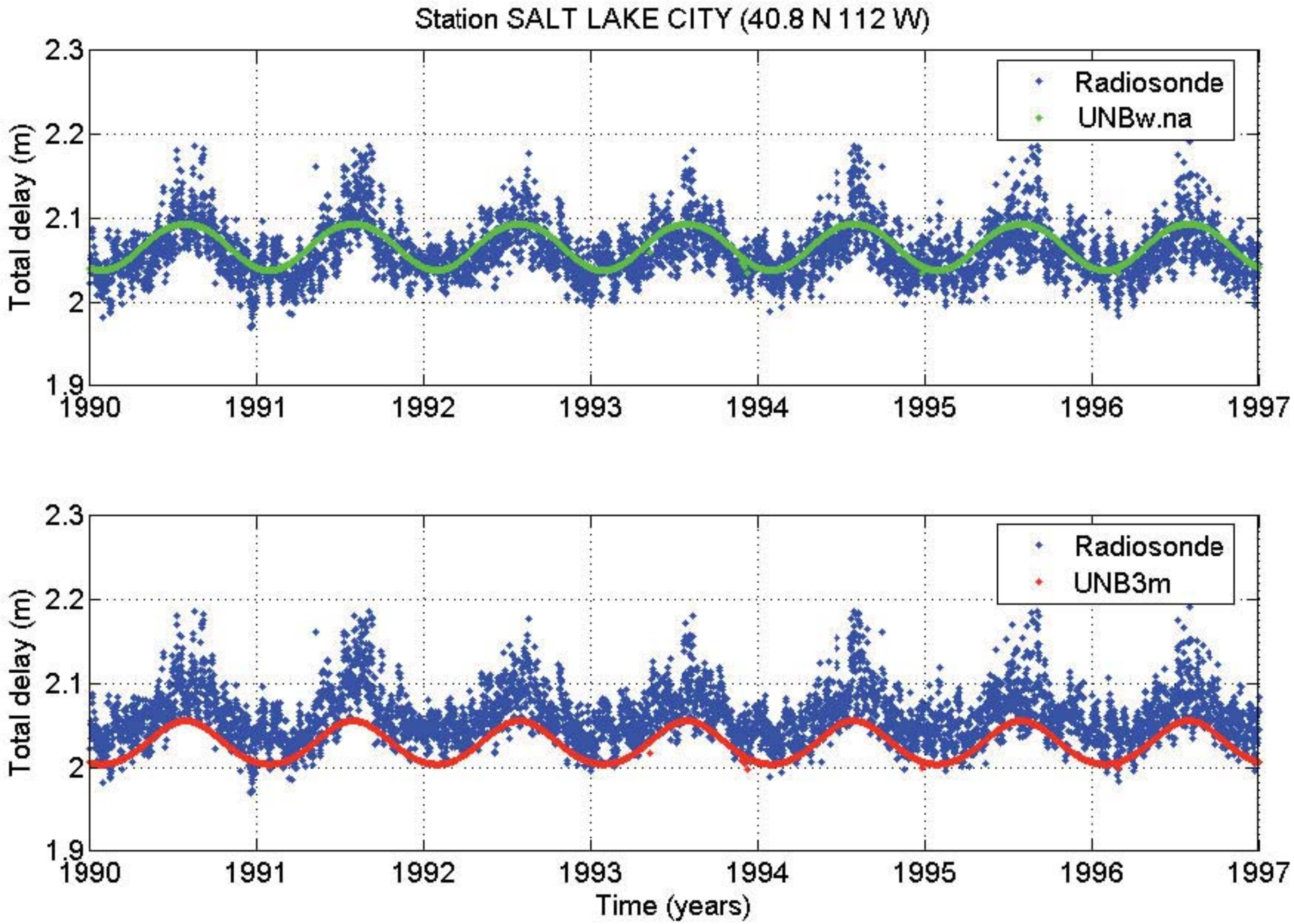
UNB3m

- In UNB3m, water vapour pressure lookup values are replaced with relative humidity values
- Standard deviation of UNB3m prediction error is similar to that of UNB3 but absolute mean error reduced by almost 75%
- Package with source code in Fortran and MatLab, UNB3m_pack, has been made publicly available (will use for lab exercise)

UNBw.na-1

- **More reliable model for wide area augmentation systems users with some homogeneity in accuracy performance over area of interest**
- **Based on actual surface meteorological values over many years rather than standard models**
- **Look-up table is a grid of values in both latitiude and longitude with spacing of 5°**
- **Initially developed for North America (0° to 90° in latitude and -180° to -40° in longitude)**

UNBw.na-2



Station SALT LAKE CITY (40.8 N 112 W)
Radiosonde
UNBw.na
Total delay (m)
2.3
2.2
2.1
2
1.9
1990
1991
1992
1993
1994
1995
1996
1997
Radiosonde
UNB3m
Total delay (m)
Time (years)

UNB3w.na-3

- **UNB3m is consistently better than UNB3m with average bias reduced by about 30% and significant predictive performance for the south-western part of the U.S. (dryer, hotter, and higher)**
- **Further details in a forthcoming paper in Navigation, the journal of The Institute of Navigation**

Neutral Atmosphere Delay Mitigation Techniques

1. No mitigation technique
2. Discard low-elevation-angle observations
3. Predict neutral atmosphere delay (NAD) using models
4. **Reduce NAD using between-receiver single differencing**
5. Estimate NAD from GPS observations
6. Measure NAD using external techniques
7. Interpolate NAD from estimates at nearby stations

Reduce NAD Using Between-Receiver Single Differencing

• This approach is used in differential GNSS positioning.

• Delay along nearby ray paths is similar, so when measurements collected at a pair of nearby receivers are differenced, the NAD remaining in the differenced observations is quite small.

• Residual delay still needs to be modelled for high-accuracy applications.

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Estimate NAD From GNSS Observations

- The zenith delay can be estimated by including it as a parameter (deterministic or stochastic) in the data processing software (parametric least squares or Kalman filter).

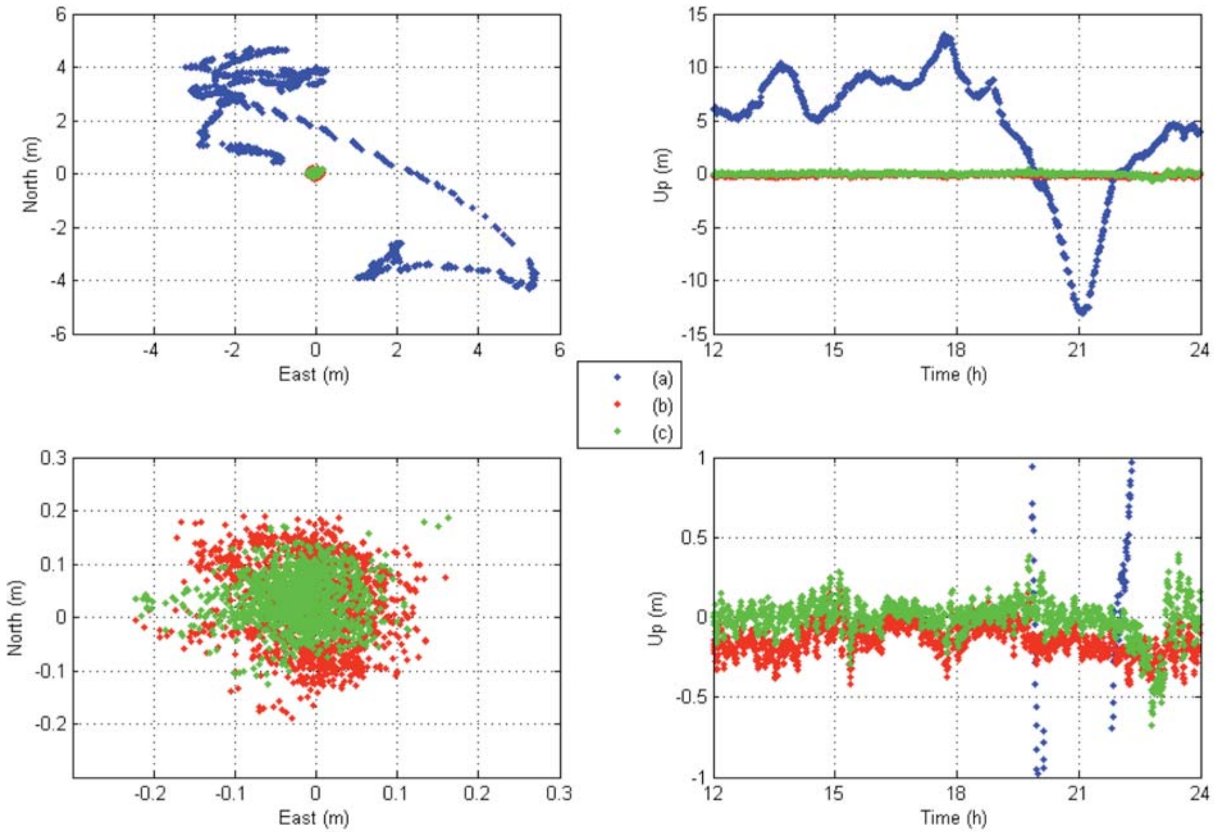
- Partial derivative of an observation with respect to the zenith delay is simply the mapping function.

A Test of Options 1, 3, and 5

Three modelling options were used to process 12 hours of GPS data from IGS station UNBJ in kinematic mode with GAPS (UNB's precise point positioning package) and the results compared with the known coordinates of the station:

(a) Not accounting for the neutral atmosphere – no corrections were applied;
(b) Accounting for the neutral atmosphere using the UNB3m prediction model (see http://gge.unb.ca/Resources/unb3m/unb3m.html);
(c) Accounting for the neutral atmosphere estimating the delay as a random walk parameter.

Precise Point Positioning Error for Different Modelling Strategies



Positioning Error Statistics

	RMS			BIAS		
	East	North	Up	East	North	Up
(a)	2.23	3.22	7.29	-0.41	1.32	4.39
(b)	0.06	0.08	0.17	-0.01	0.03	-0.15
(c)	0.05	0.06	0.12	-0.02	0.03	-0.01

(all units are metres)

Gradient Models

• Many neutral atmosphere delay models assume azimuthal symmetry; i.e., the atmosphere is assumed to be the same all around a site.
• Clearly this doesn't match reality particularly during the passage of weather fronts.
• Models have been enhanced by including gradient terms that can be estimated from the GNSS data.

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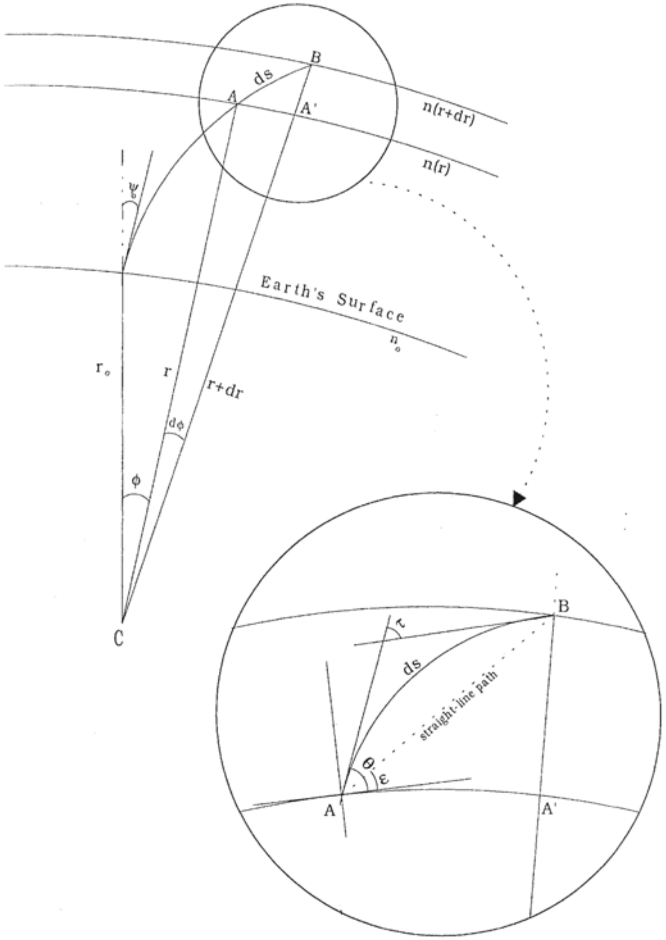
Ray Tracing Through Radiosonde Profiles or Numerical Weather Models



- Radiosondes (also known as weather balloons) are launched from many locations around the world twice a day.

- Pressure, temperature, and relative humidity measurements are send by radio to the ground.

- The profiles can be used to determine refractivity at points along a path entering or leaving the atmosphere at a particular elevation angle.

- The same procedure can be used with numerical weather models.

Water Vapour Radiometer

- **Measures brightness temperature at two or more frequencies near and adjacent to the water vapour line**
- **Radiometrics WVR-1100 uses 23.8 and 31.4 GHz**
- **Measurements converted to wet tropospheric delay along direction of measurement using calibration constants**

- **Accuracies typically better than 1 centimetre**

Neutral Atmosphere Delay Mitigation Techniques

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Interpolate NAD From Estimates at Nearby Stations

• This approach is used in real-time differential GNSS, such as DGPS and real-time kinematic (RTK) positioning.

• In pseudorange-based DGPS, the transmitted correction includes the effect of NAD as experienced at the reference station.

• In network RTK, an interpolated zenith NAD can be sent to the user.

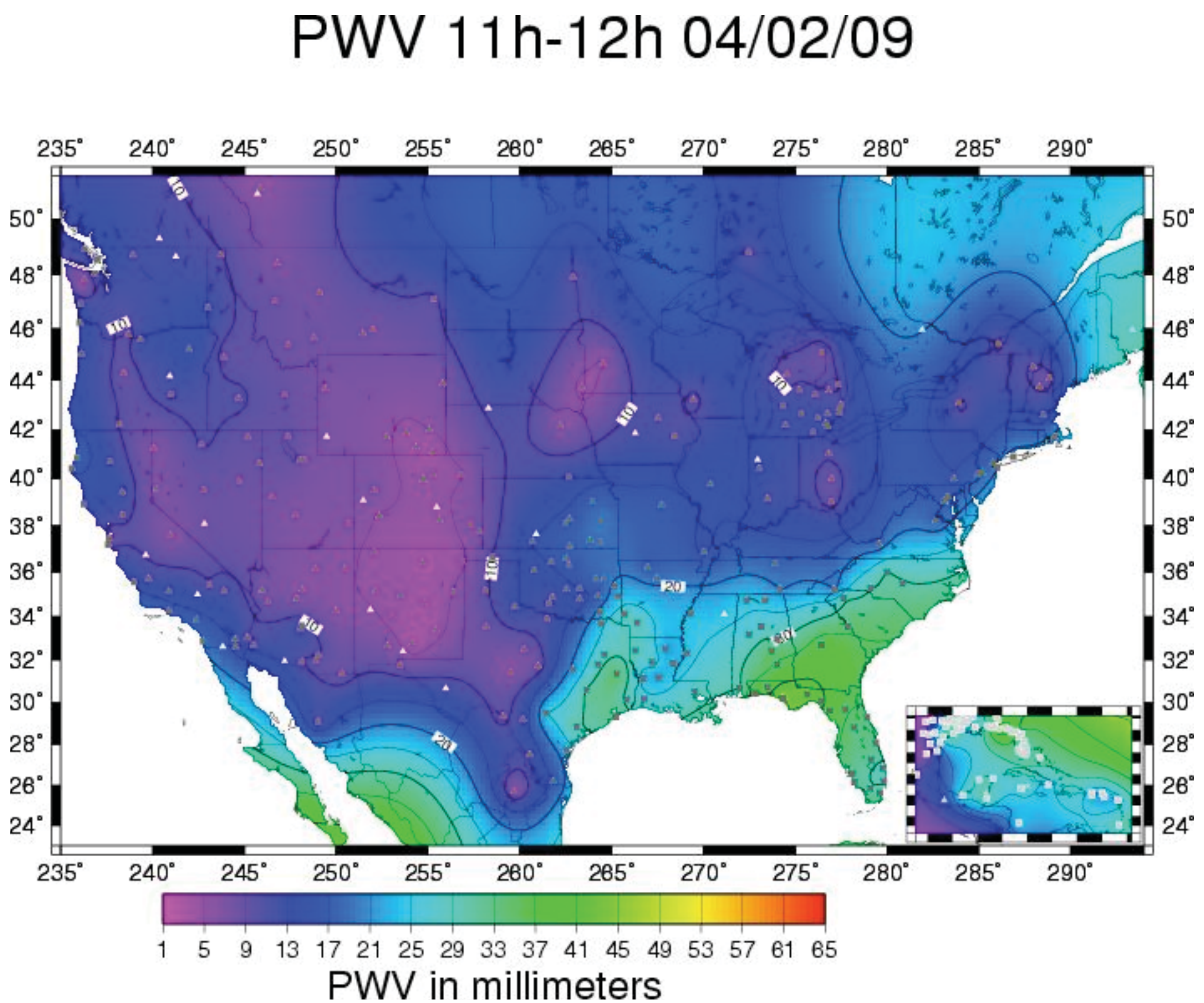
Using GNSS to Measure Atmospheric Moisture Content

- Precipitable water (vapour), the total atmospheric water vapour in a vertical column of unit cross-sectional area in terms of the height to it would stand if completely condensed and collected in a vessel of the same unit cross section (PW), is proportional to the zenith wet delay (ZWD)
- ZWD is estimated from GNSS measurements after removing hydrostatic delay computed from accurate surface pressure measurements
- 10 mm PW corresponds to about 65 mm of ZWD
- 1 mbar error in surface pressure could result in 0.4 mm error in precipitable water

Monitoring Networks

Several GNSS monitoring networks have been established in different parts of the world for determining precipitable water; e.g., the University Corporation for Atmospheric Research (UCAR) SuomiNet, the U.S. National Oceanic and Atmospheric Administration's Global Systems Divison Ground-Based GPS Meteorology (GPS-MET), etc.

SuomiNet



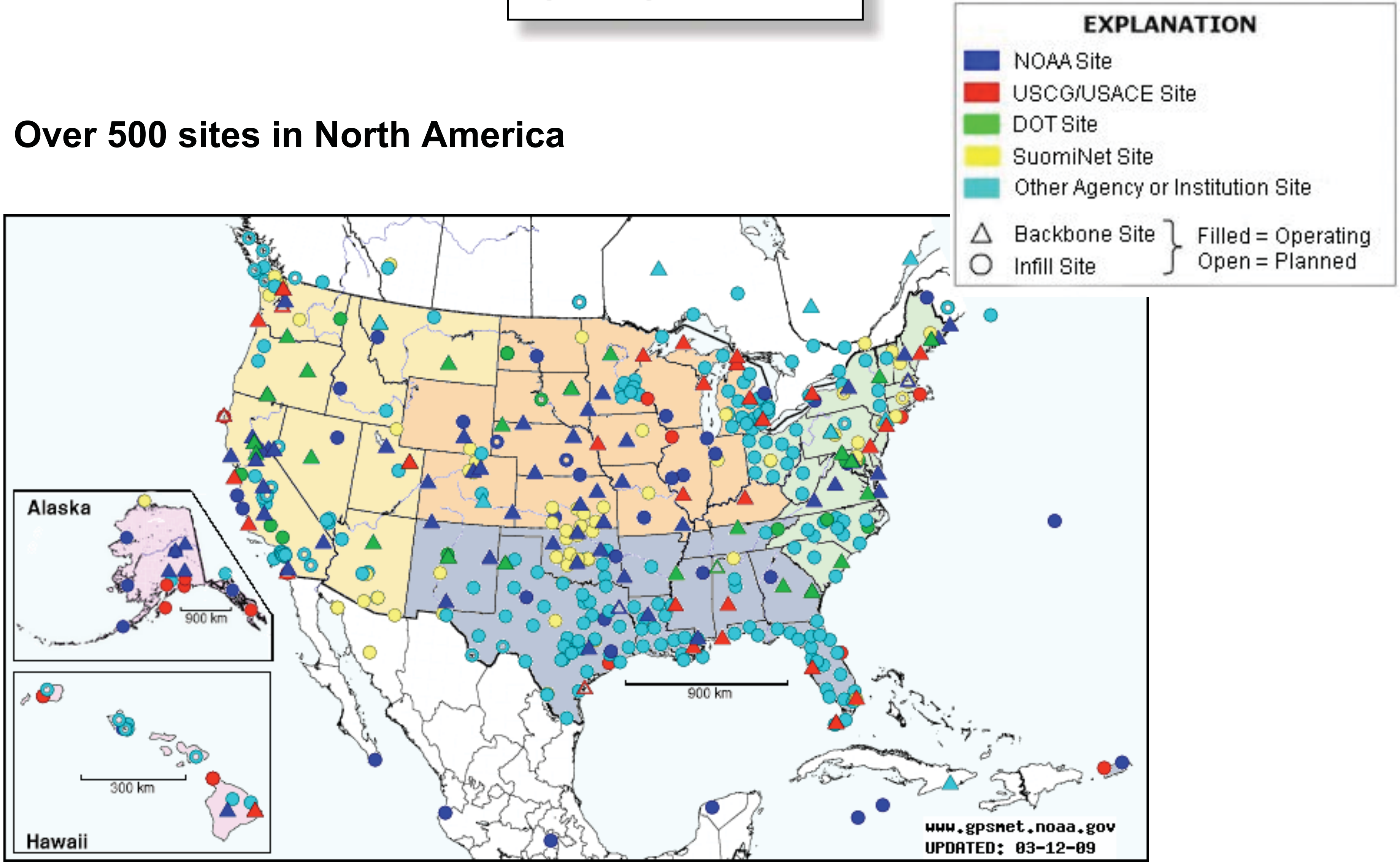
About 60 sites in the U.S.A., Canada, and the Caribbean

Sites use Trimble equipment and most have auxiliary met sensors

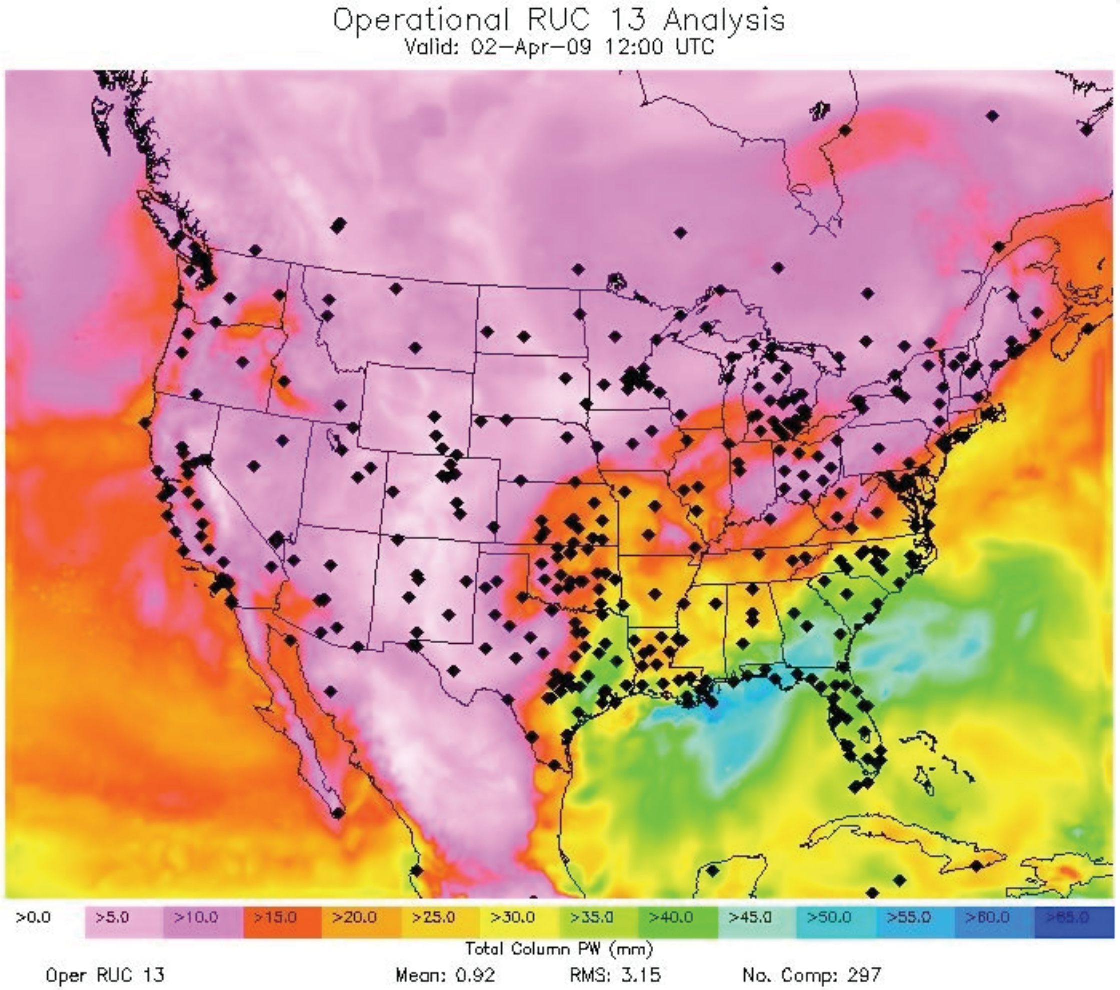
Animation:http://www.unidata.ucar.edu/data/suominet/loop/suomi_ani.html

GPS-MET

Over 500 sites in North America



Rapid Update Cycle (RUC) Weather Prediction

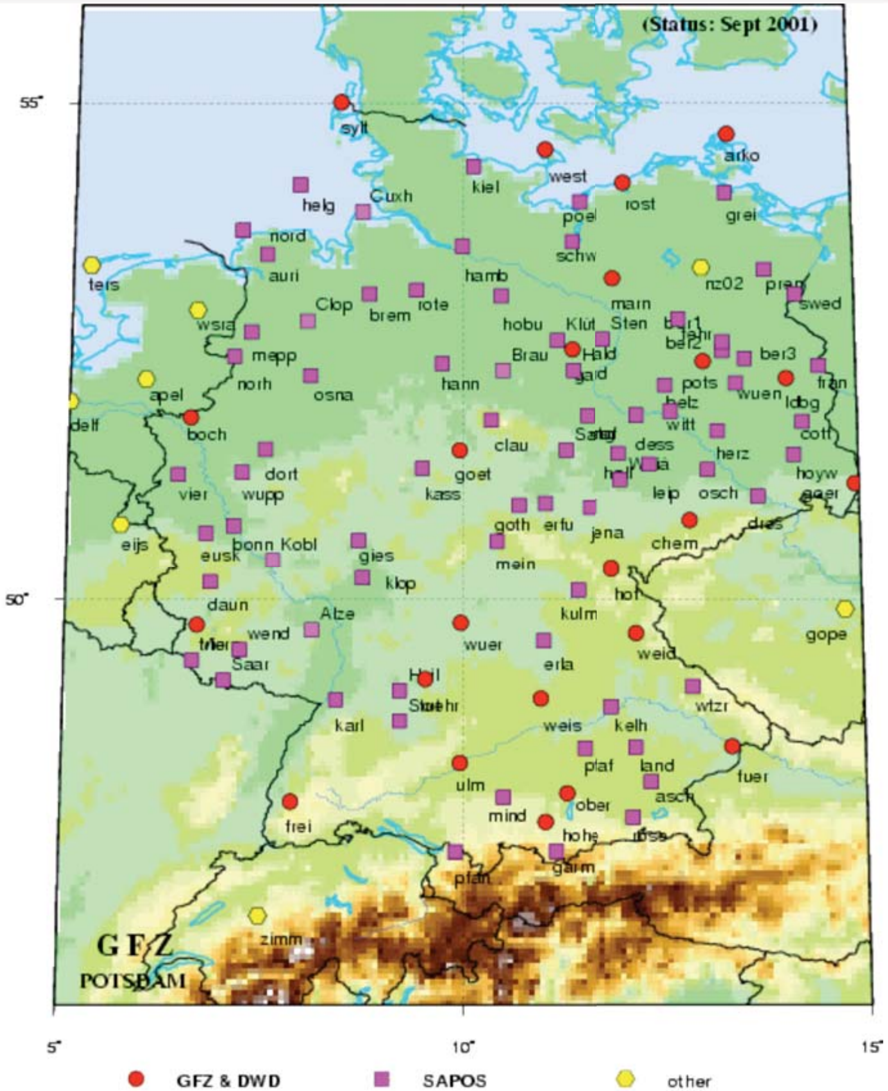


RUC 13 = 13 km resolution model, updated hourly with predictions out to 12 hours +

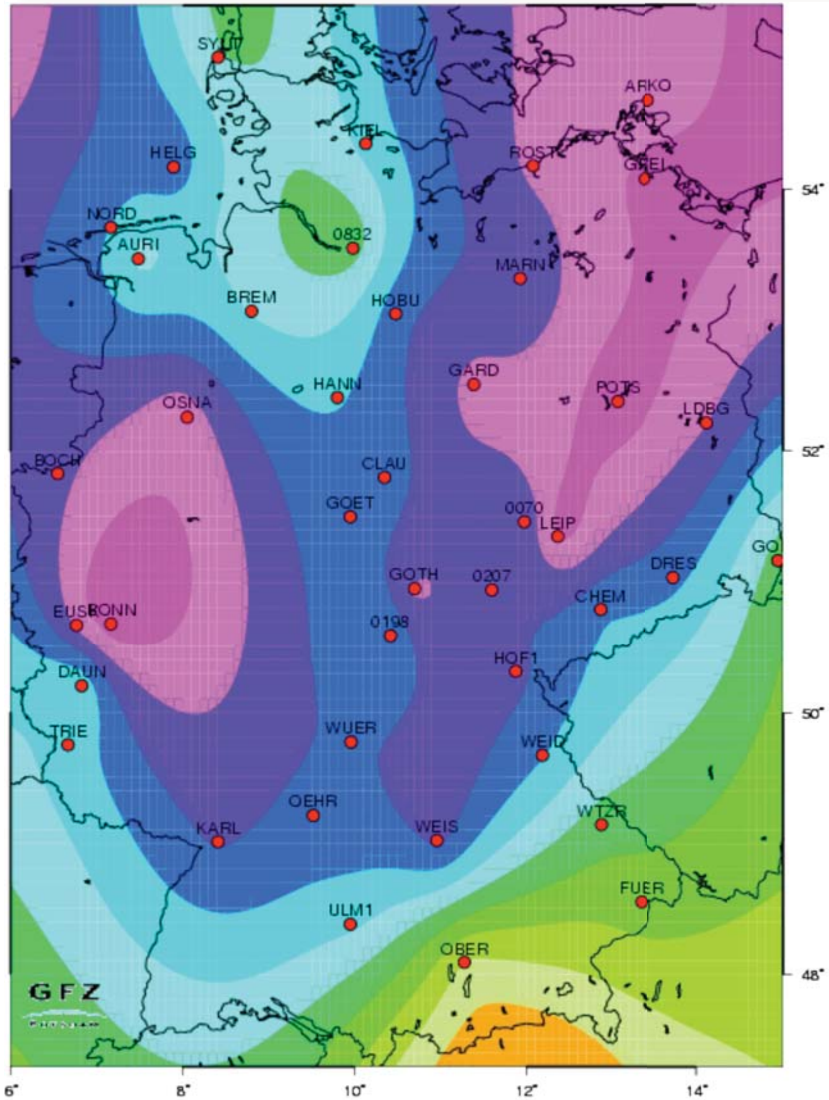
Hurricane Forecasting

animation:
http://gpsmet.fsl.noaa.gov/jsp/katrina2.jsp

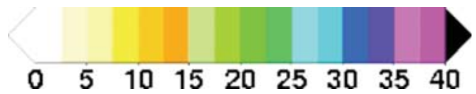
German GPS Met Network



Estimated Water Vapour Field



15 August 2000
12:00 UT



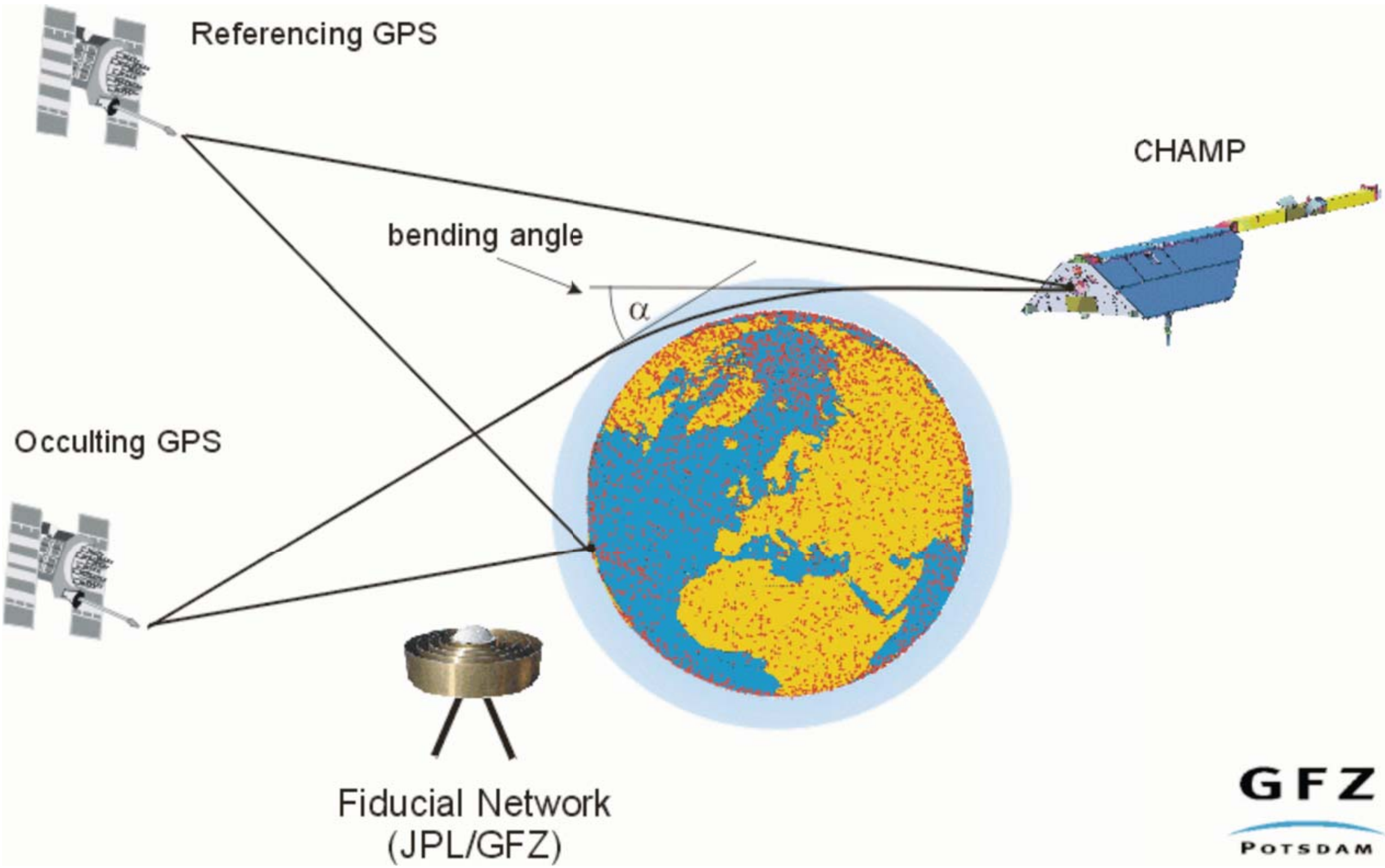
IWV(kg/m²)

Integrated water vapour (IWV)
= PWV • density of H_2O

Atmosphere Profiling Using GNSS Receivers Onboard LEO Satellites

- Dual-frequency GNSS receiver on low Earth orbiting (LEO) satellite
- Signal raypaths of rising and setting GNSS satellites as viewed from the LEO are bent by the atmosphere
- The bending angle can be measured and related to the refractive index at the height of the ray
- Refractive index can be interpreted to give profiles of temperature

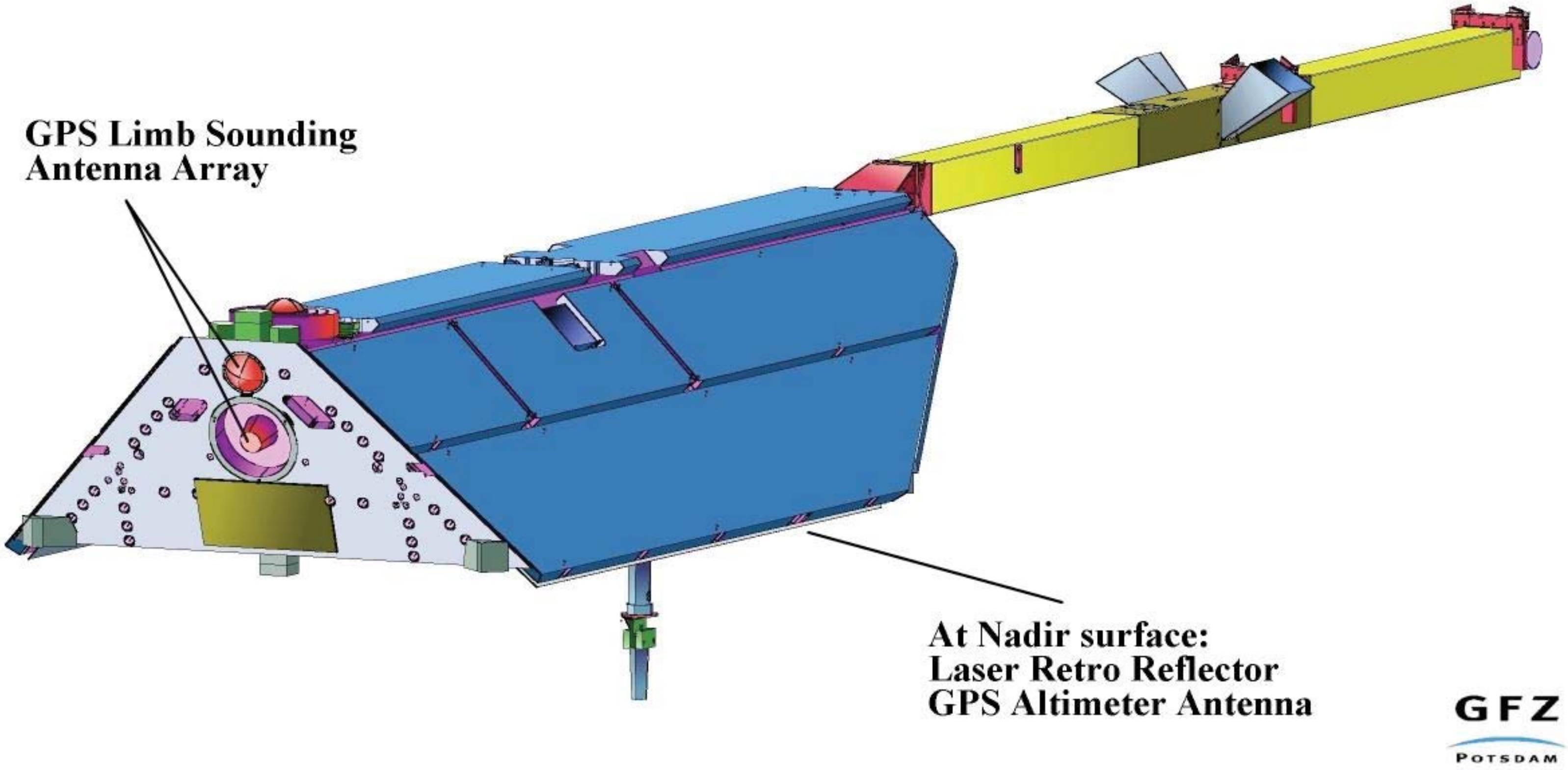
Spaceborne GPS Limb Sounding



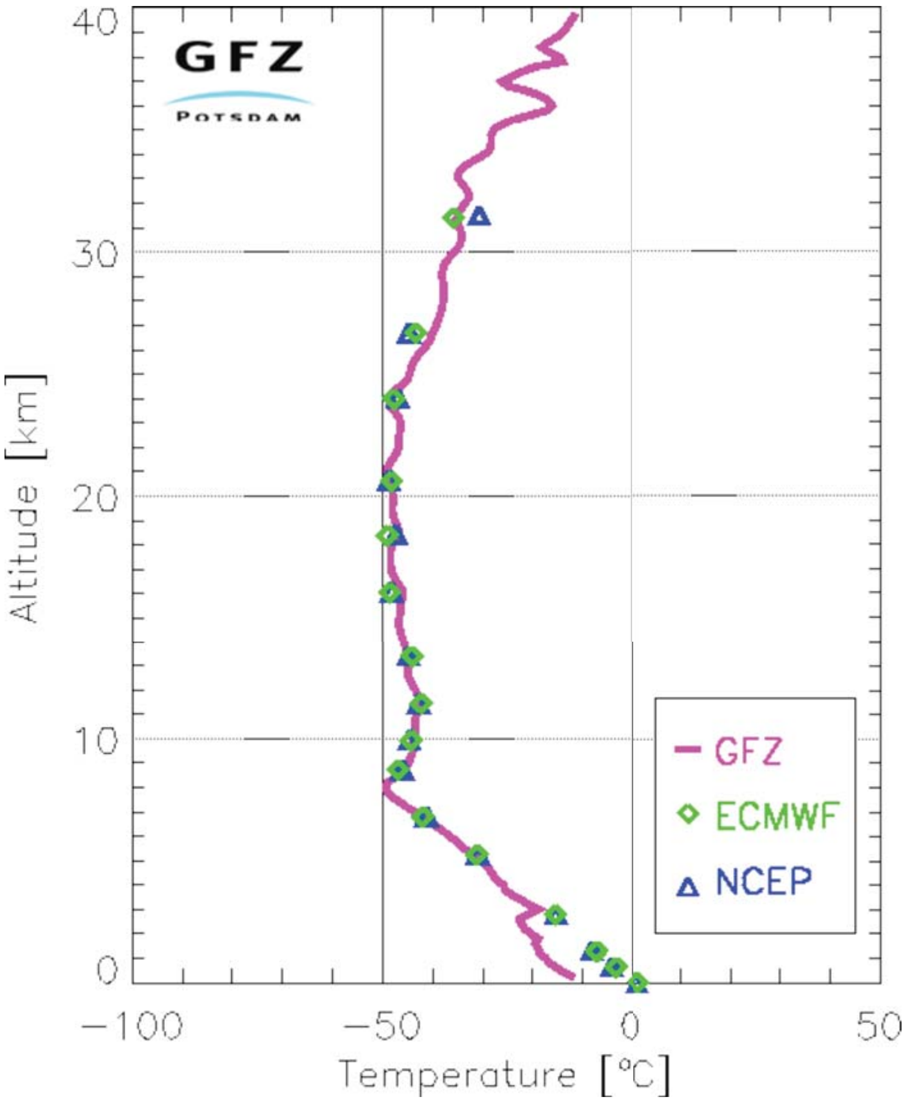
LEO Atmospheric Profiling Satellites

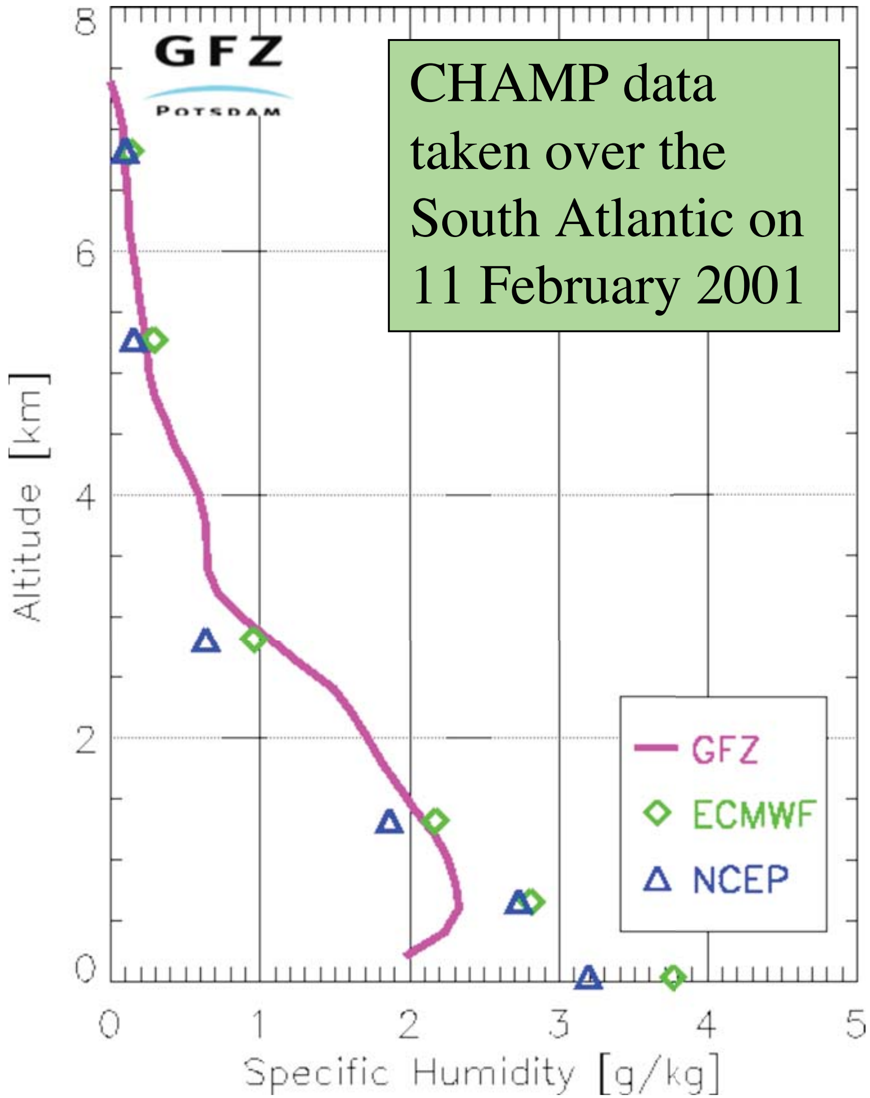
A number of satellites with this capability have been launched:
GPS-Met, U.S.A. (1995)
CHAMP, Germany (2000)
SAC-C, Argentina (2000)
COSMIC (6 satellites), Taiwan and U.S.A. (2006)
METOP-A, Europe (2006)
…

CHAMP


GPS Limb Sounding
Antenna Array
At Nadir surface:
Laser Retro Reflector
GPS Altimeter Antenna
GFZ
POTSDAM

CHAMP Profiling





CHAMP data taken over the South Atlantic on 11 February 2001

What Have We Learned?

• The physics of the propagation of radio signals through the neutral atmosphere.

• How the neutral atmosphere affects GNSS measurements.

• How to mitigate the effects of the neutral atmosphere in GNSS positioning.

• How GNSS signals can be used to remotely sense atmospheric properties.

Practical Lab

In the lab, you will download UNB3m_pack, a neutral atmosphere delay package for radiometric space techniques, and work with it in the MatLab programming environment to see how the prediction of delays varies with location, station height, and day of year.

Thanks, Grazie, Ahsante