GNSS radio occultation (GNSS-RO): Lecture 1 – Principles and NWP use

ECMWF/EUMETSAT Satellite training course. March 24, 2026

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EUMETSAT
ROM SAF
RADIO OCCULTATION METEOROLOGY

https://rom-saf.eumetsat.int/

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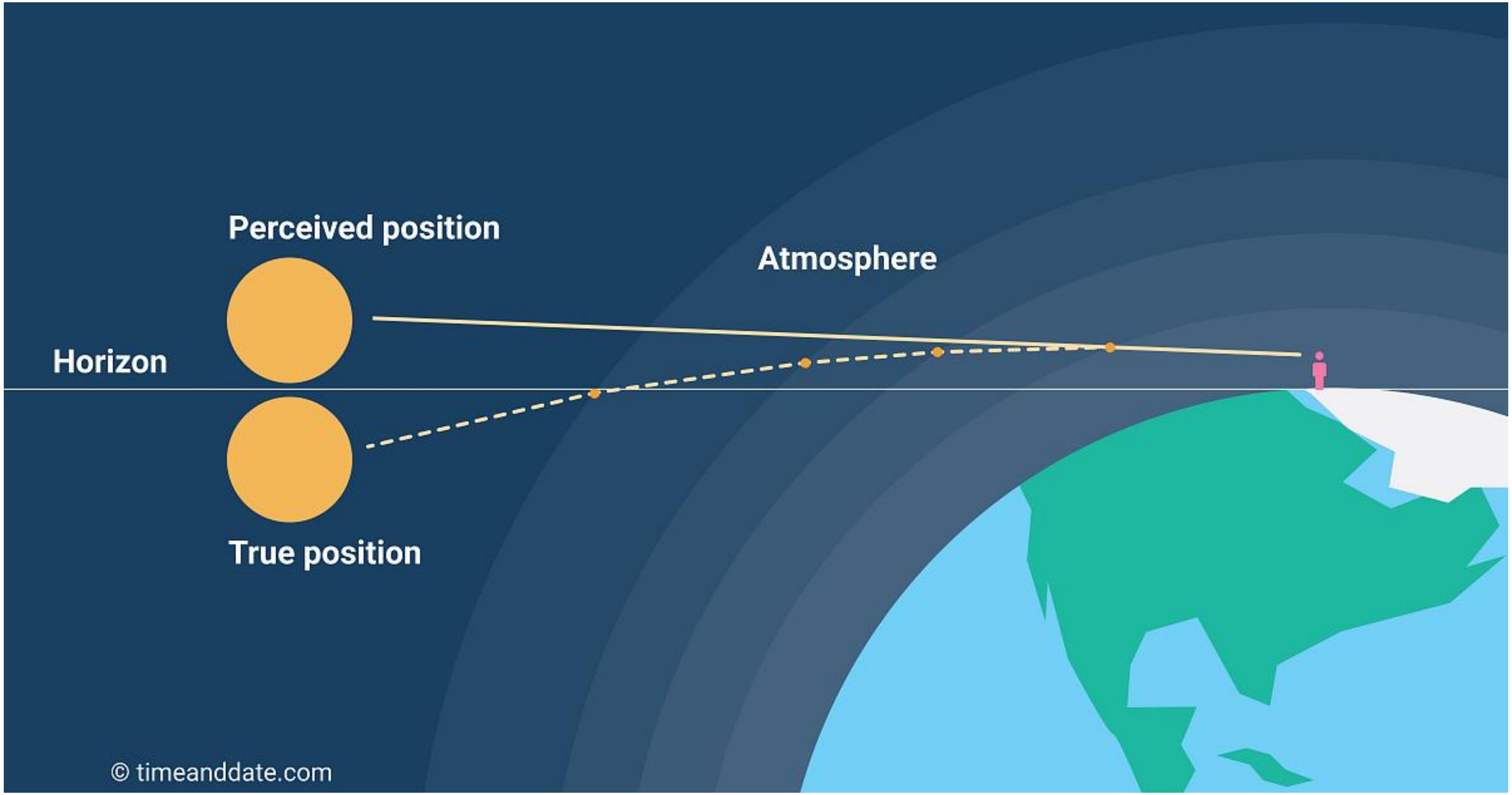
Actually, the sun is already below the horizon.

Atmospheric refraction



Outline

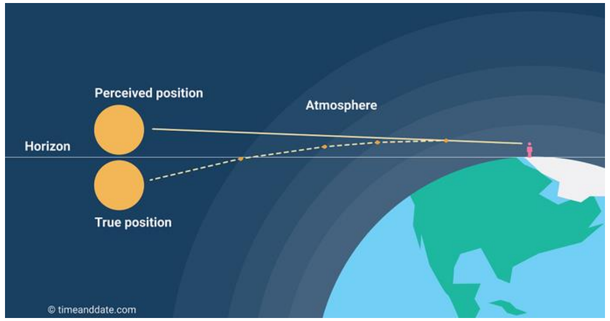
- **GNSS-RO Principles**
  - GNSS **measurement geometry**.
  - **Basic physics**, some history …
  - GNSS radio occultation and “**Classical**” **GNSS-RO temperature retrieval.**
  - Some **limitations**.

- **Assimilation of GNSS-RO data**
  - **Information content** and resolution estimates from 1D-Var.
  - **4D-Var** assimilation of GNSS-RO measurements (GNSS-RO null space).
  - Move to more complicated **2D operators**.

- **Summary and conclusions.**

- **Lecture 2 will cover forecast impact, reanalysis applications, climate trends, etc.**

GNSS-RO Principles



GNSS-RO Principles

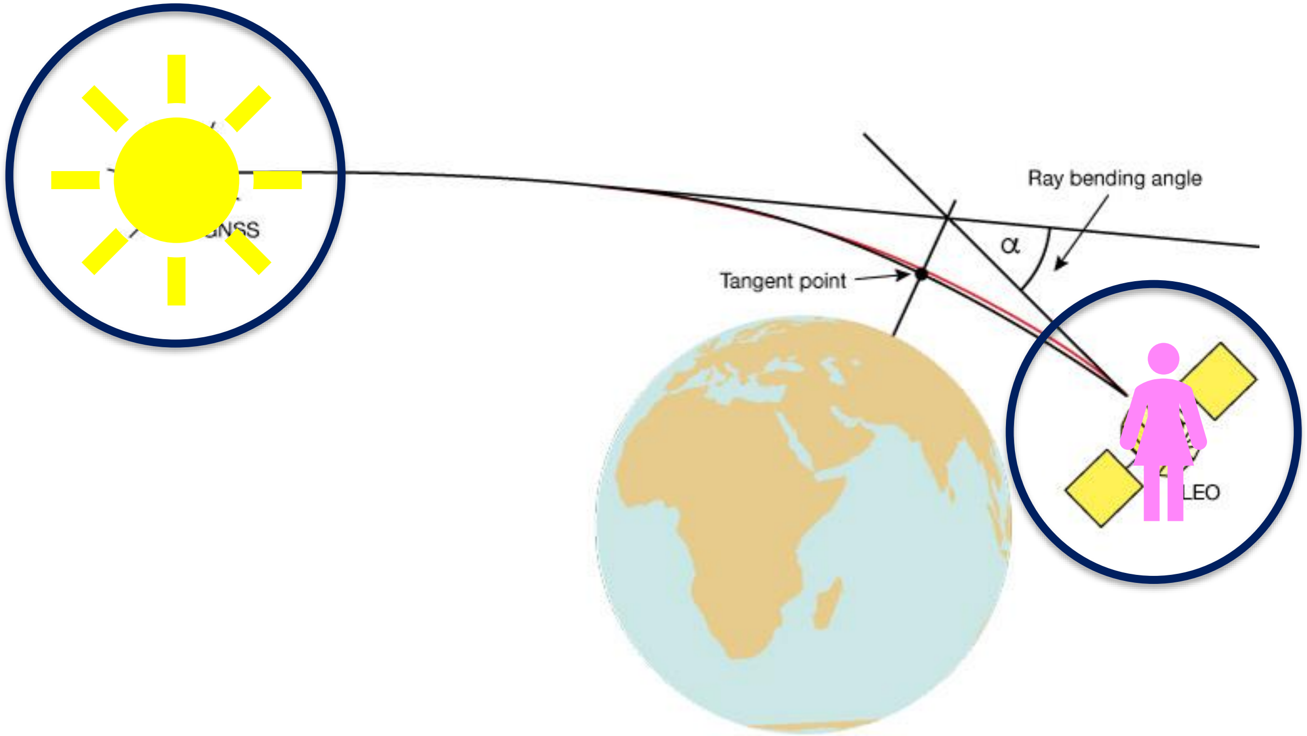
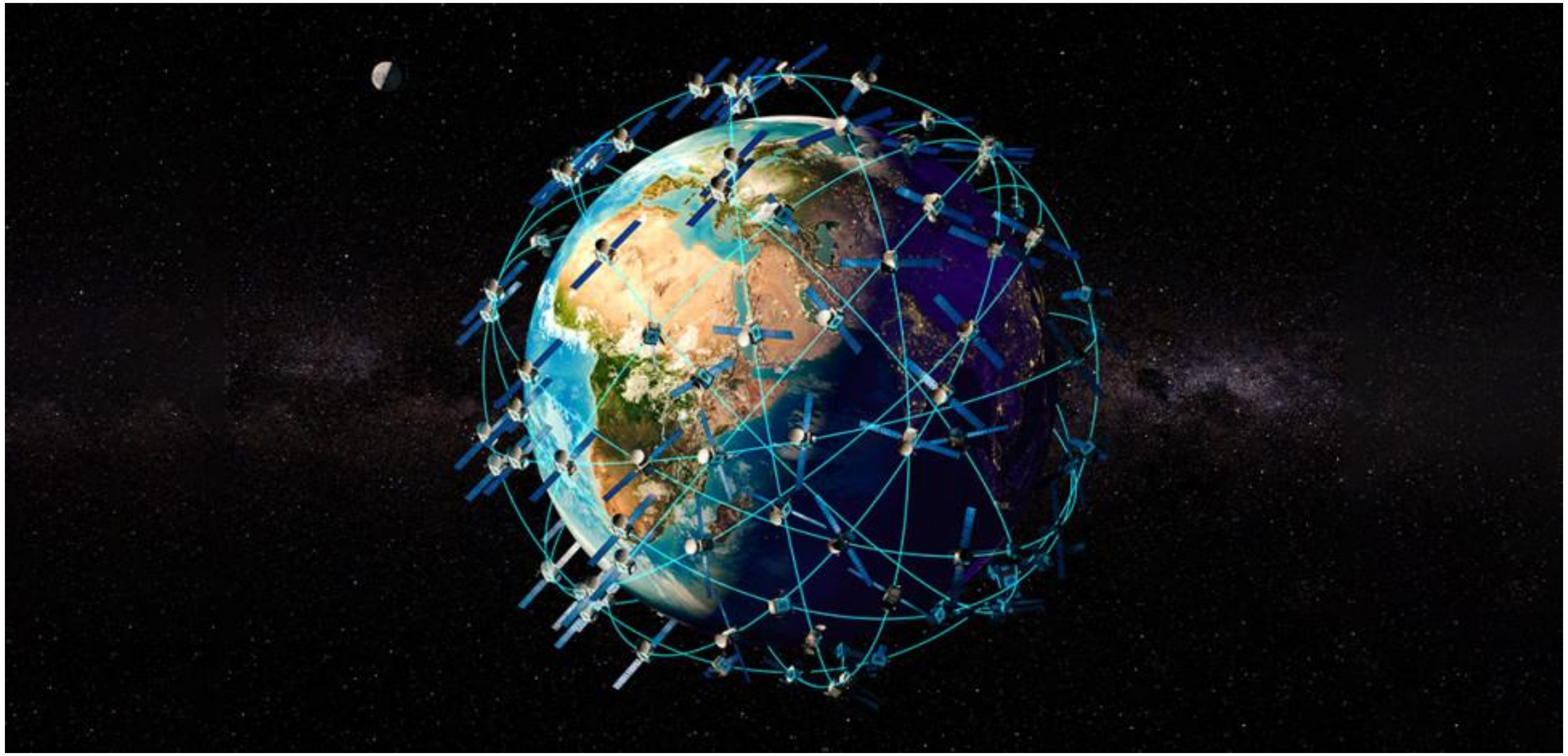


Fig. taken https://www.spirent.com/blogs/what-is-the-difference-between-gnss-and-gps on 4 March 2022

What are GNSS, GPS etc.?

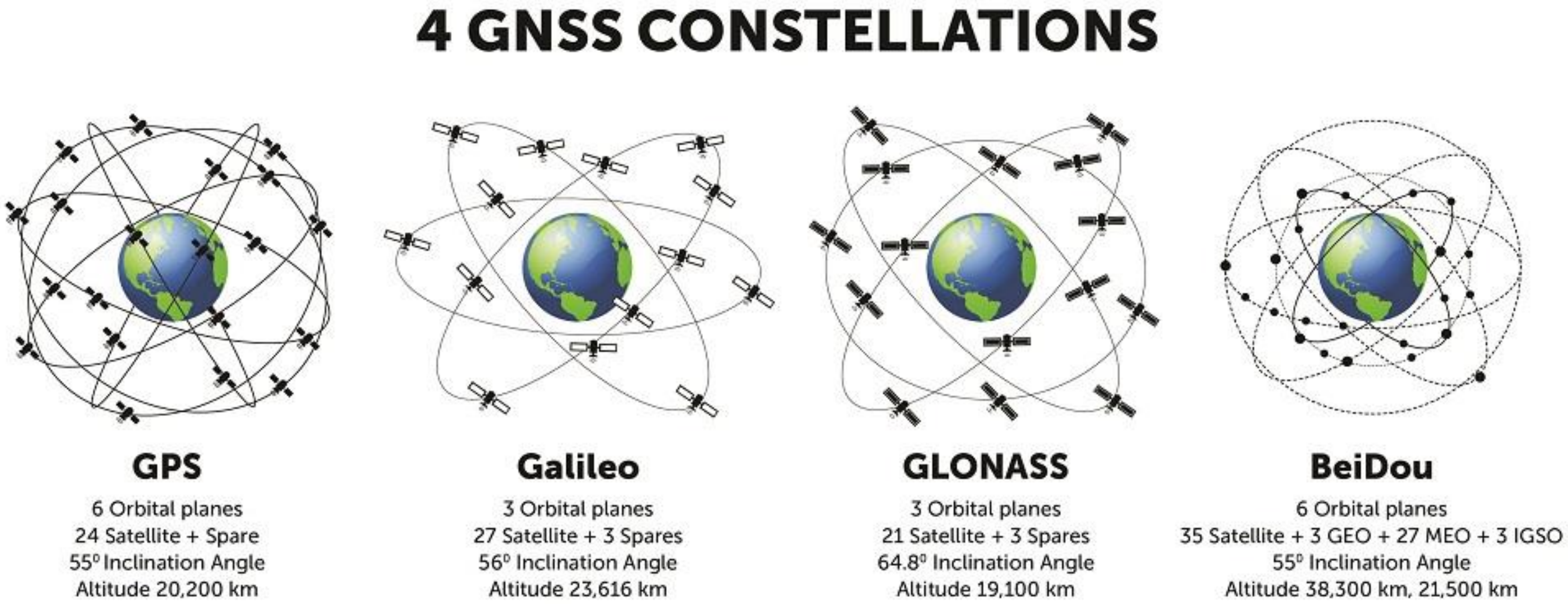
GNSS (Global Navigation Satellite System)
is a generic name for any system where satellite signals are used for navigation globally.

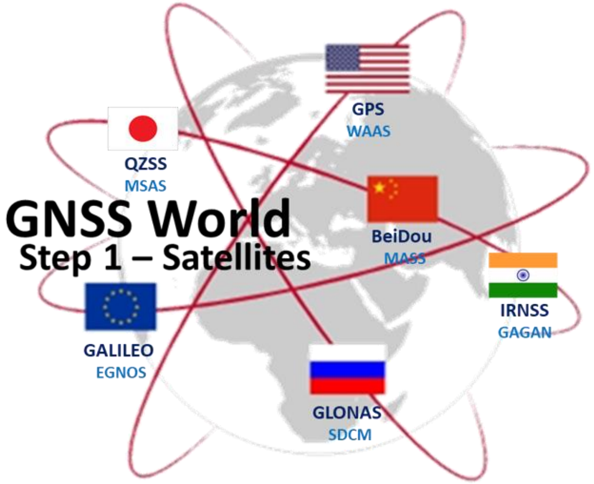


Satellites in Medium Earth Orbit (~20,000km) emit radio signals.
For navigation purposes, the time taken to receive the signals from multiple satellites is used to calculate the position of the receiver.

What are GNSS, GPS etc.?

Figure from an article by https://spacenews.com/modern-civilization-would-be-lost-without-gps/ on 3.8.2021

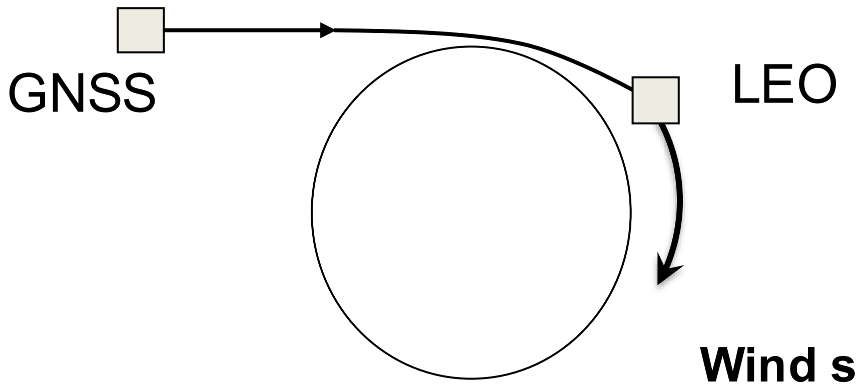




- **GPS** (Global Positioning System) is the original US system and by far the most widely used (e.g. satnavs).
- **Galileo** is a European GNSS system.
- **GLONASS** is the Russian system (COSMIC-2 and Spire have a GLONASS capability).
- **BeiDou** is the Chinese system (and includes geostationary satellites).
- **QZSS** is the regional satellite system from Japan
- **IRNSS** provides service to India and the surrounding area

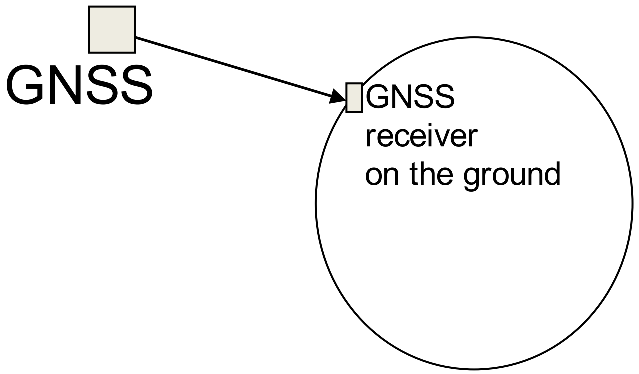
Atmospheric measurements made using GNSS signals – three types

GNSS Radio Occultation (profile information from the atmospheric limb)

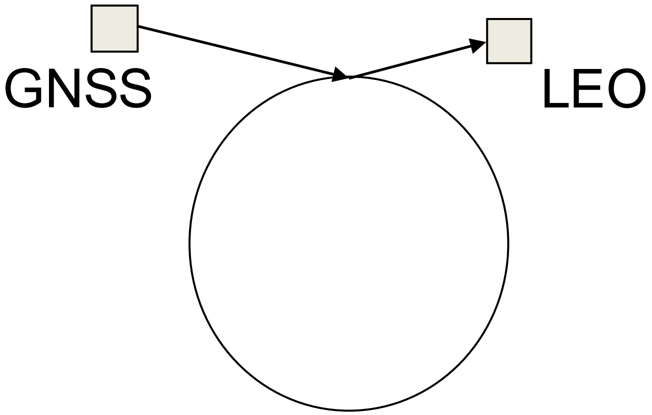


GNSS Receiver
placed on satellite in
Low Earth Orbit (LEO)

Ground-based GNSS
(Column integrated water vapour)



Wind speed information from signal reflected from ocean surface(“GNSS-reflectometry”)



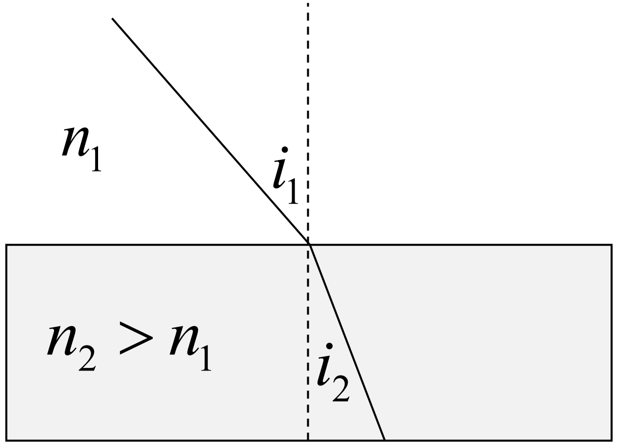
The basic GNSS-RO physics – Snel's Law

- **Refractive index**: Speed of an electromagnetic wave in a vacuum divided by the speed through a medium.

$$\boxed{n = \frac{c}{\mathrm{v}}}$$

- Snel's Law of refraction – bending occurs when refractive index changes. In the atmosphere the refractive index varies continuously.

$$\boxed{n_1 \sin i_1 = n_2 \sin i_2}$$

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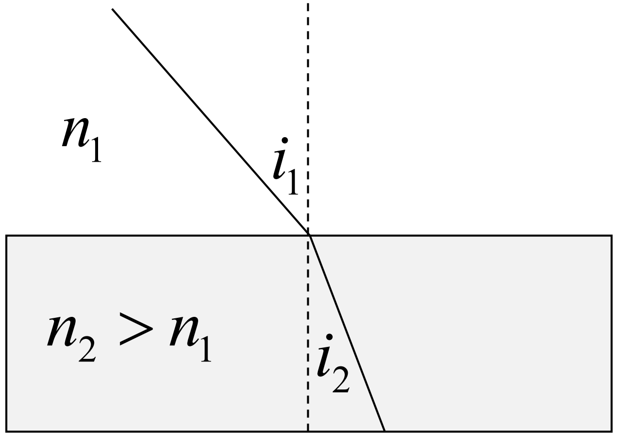
The basic GNSS-RO physics – Snel's Law

- **Refractive index**: Speed of an electromagnetic wave in a vacuum divided by the speed through a medium.

$$n = \frac{c}{v}$$

In the atmosphere, the refractive index varies smoothly, though sharp gradients can occur.

$$n_1 \sin i_1 = n_2 \sin i_2$$

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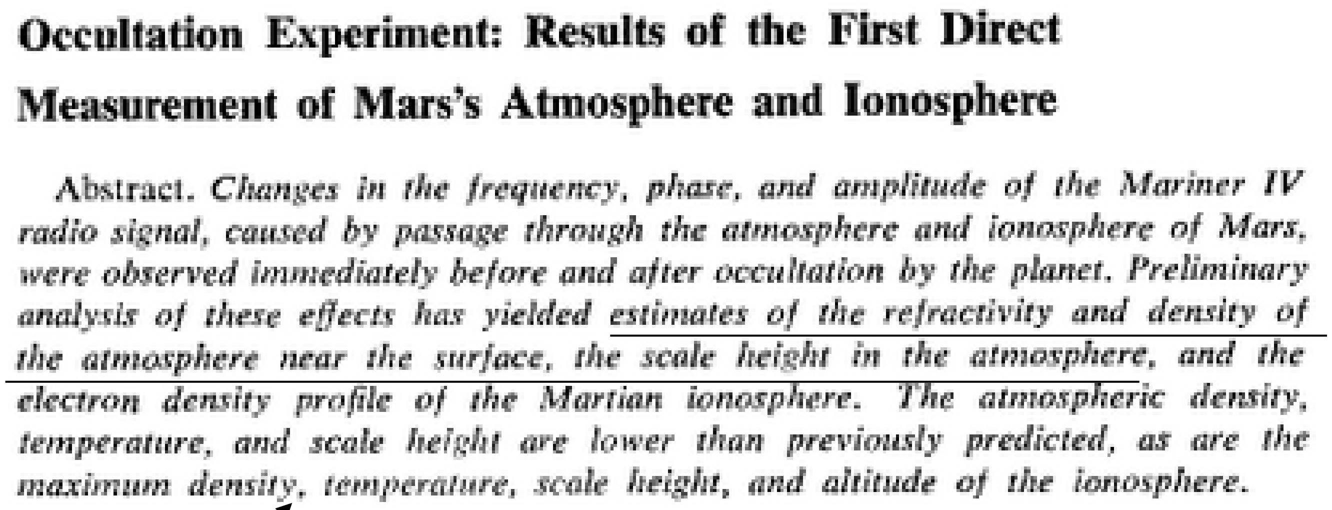
Radio Occultation: Some Background (1)

Radio occultation (RO) measurements have been used by to study planetary atmospheres (**Mars, Venus**) since the 1960s. It is an **active technique**. The paths of radio signals are **bent by refractive index gradients** in the atmosphere/ionosphere.



Occultation Experiment: Results of the First Direct Measurement of Mars's Atmosphere and Ionosphere

Abstract. *Changes in the frequency, phase, and amplitude of the Mariner IV radio signal, caused by passage through the atmosphere and ionosphere of Mars, were observed immediately before and after occultation by the planet. Preliminary analysis of these effects has yielded estimates of the refractivity and density of the atmosphere near the surface, the scale height in the atmosphere, and the electron density profile of the Martian ionosphere. The atmospheric density, temperature, and scale height are lower than previously predicted, as are the maximum density, temperature, scale height, and altitude of the ionosphere.*

Fjeldbo et al 1970

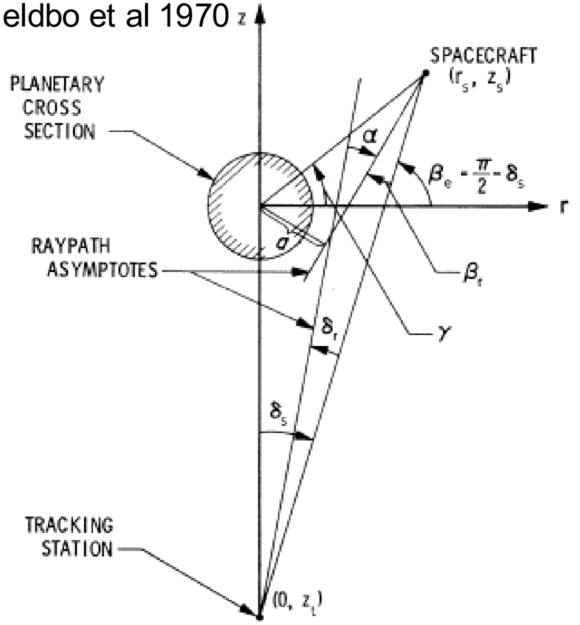
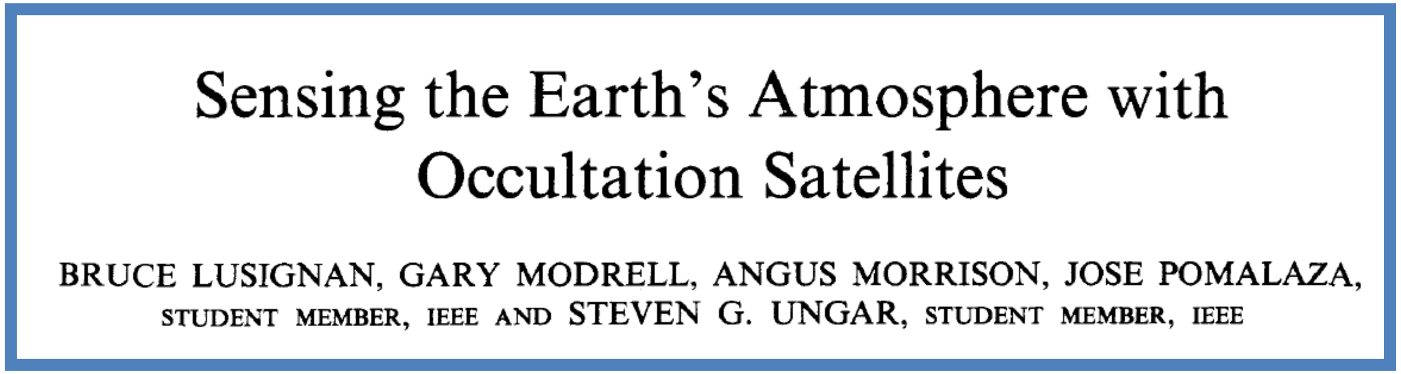


Fig. 20. Occultation geometry: The illustrated ray path is bent in the ionosphere where the refractive index is less than 1.

Kliore et al Science, 1965, Vol. 149, No. 3689, pp. 1243-1248

Radio Occultation: Some Background (2)

The use of RO measurements in the Earth’s atmosphere was originally proposed in **1969 (Proceedings of the IEEE, vol. 57, no. 4, pp. 458-467, *1969!*)**



Sensing the Earth’s Atmosphere with Occultation Satellites

BRUCE LUSIGNAN, GARY MODRELL, ANGUS MORRISON, JOSE POMALAZA,
STUDENT MEMBER, IEEE AND STEVEN G. UNGAR, STUDENT MEMBER, IEEE

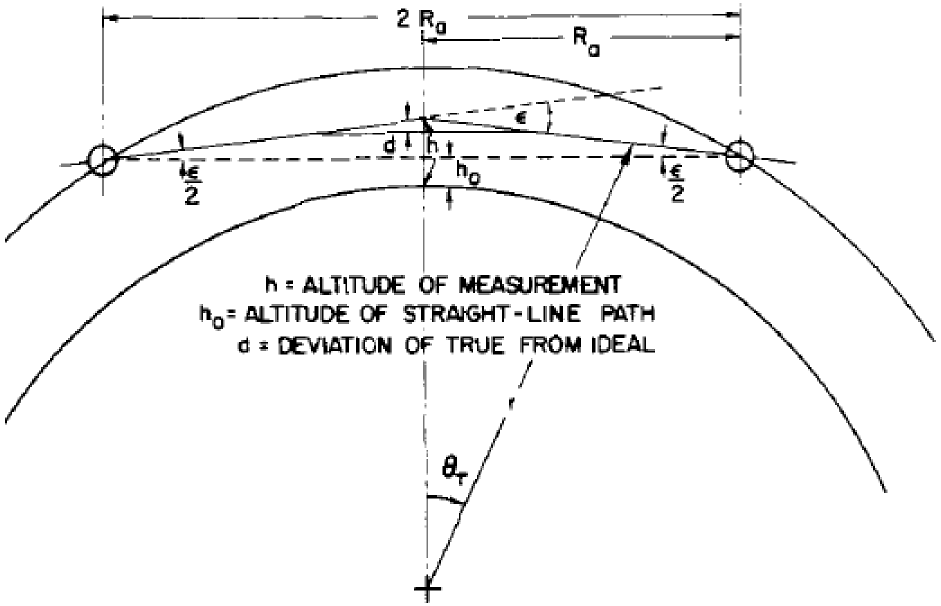


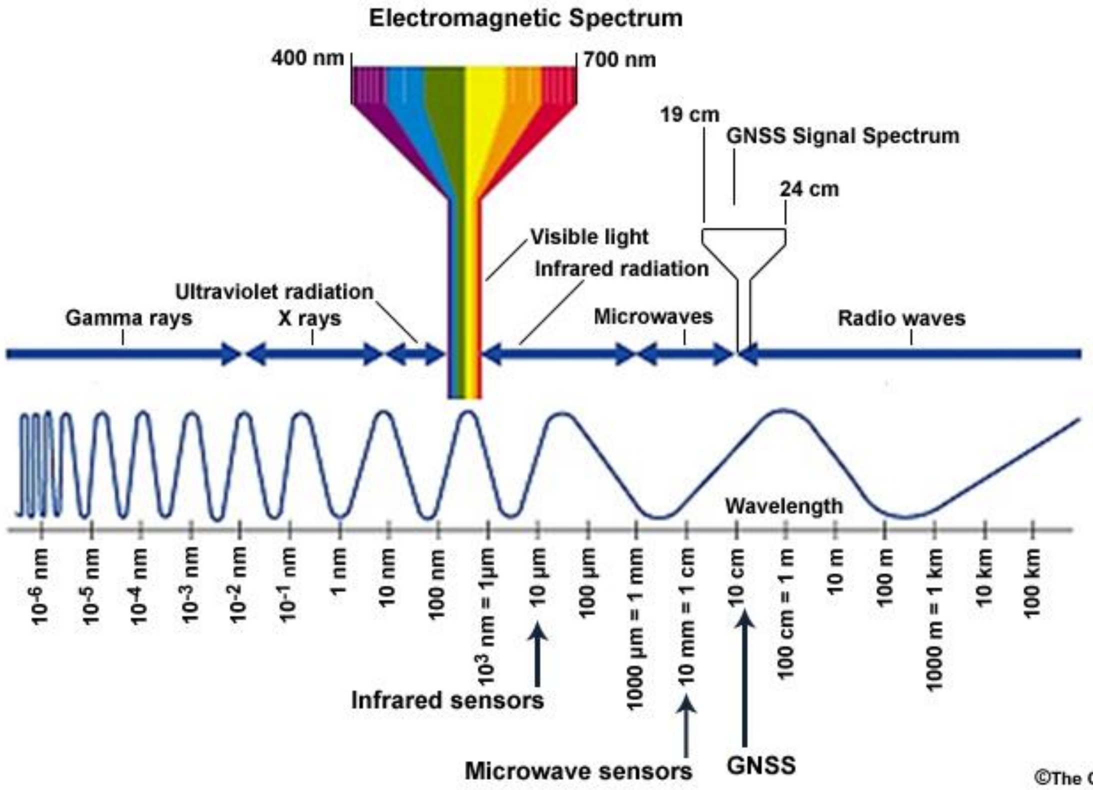
Fig. 1. Basic geometry of occultation measurement.

Radio Occultation: Some Background (3)

- The ideas outlined in 1969 seem to have got lost. Probably because the costs looked prohibitive.
- … but then the GPS constellation was launched in the 1980s – an excellent, free source of radio waves for RO.
- Use of **GPS** signals for RO discussed at the Jet Propulsion Laboratory (JPL) in late 1980s (e.g. Tom Yunck).
- In **1996** the proof of concept atmospheric RO experiment, "GPS/MET", – funded by the US NSF – demonstrated useful temperature information could be derived from the GPS-RO measurements.

GNSS-RO: Basic idea

The GNSS satellites are primarily a tool for positioning and navigation These satellites emit **radio signals** at L1= 1.57542 GHz and L2=1.2276GHz (~20 cm wavelength).



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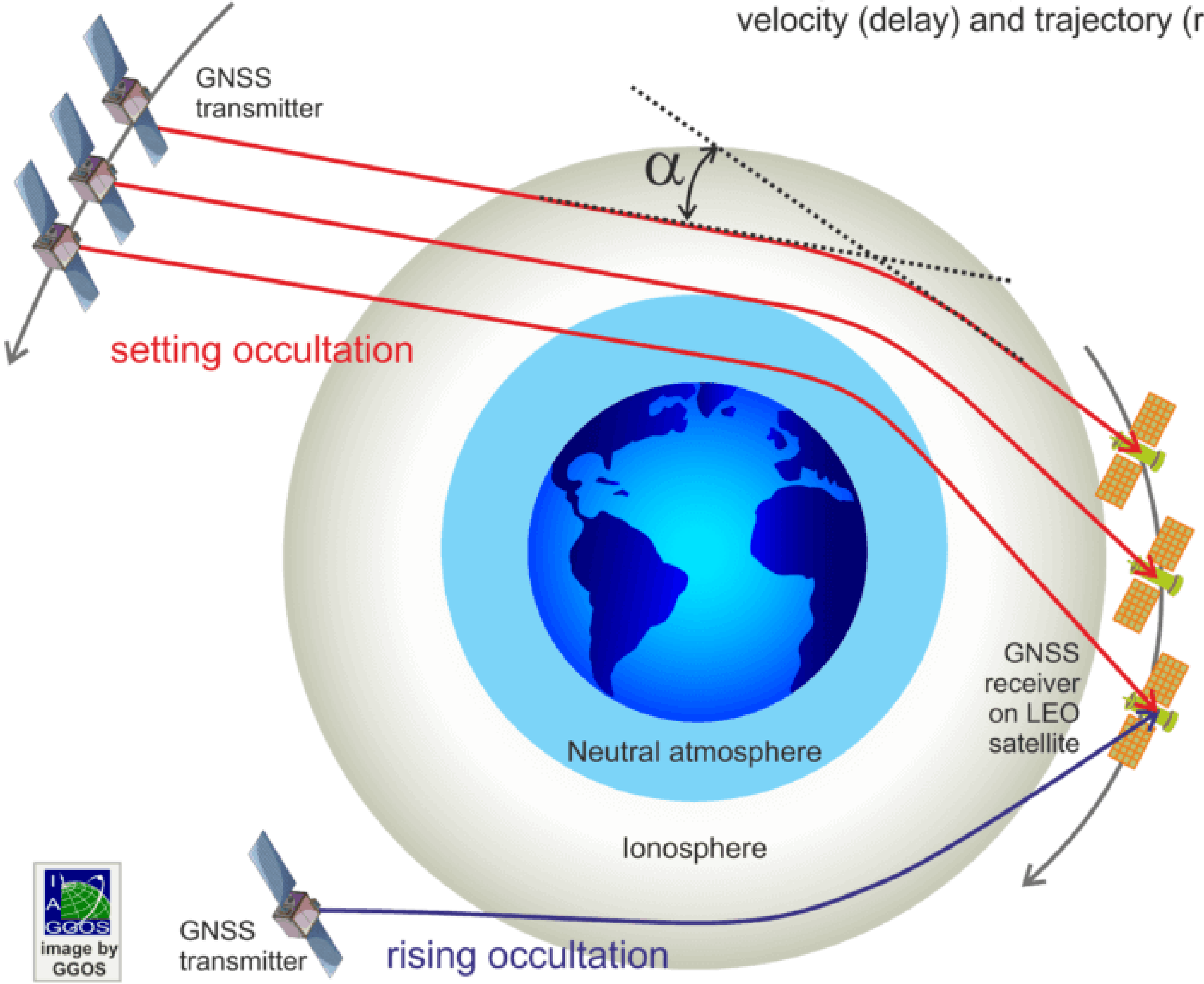
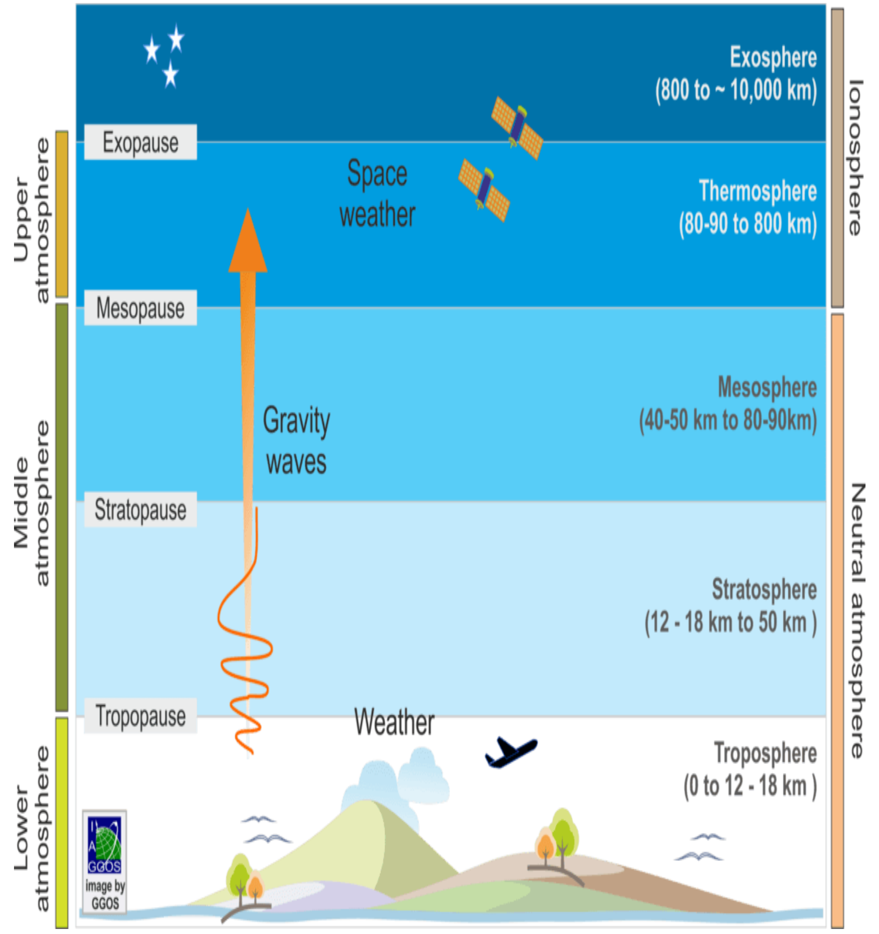
GNSS satellites continuously emit radio signals. When propagating through the atmosphere, these signals experience changes in velocity (delay) and trajectory (refraction).





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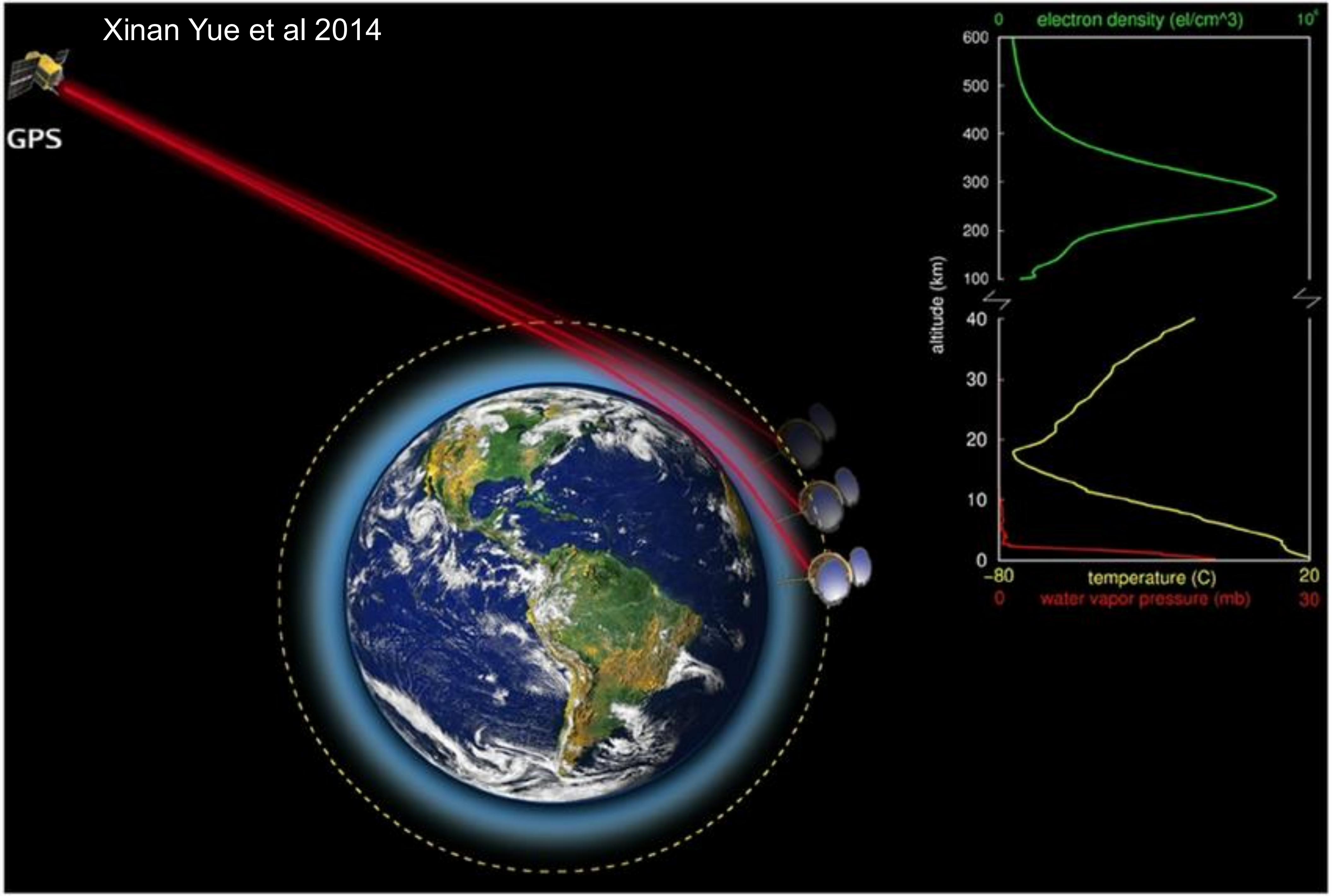
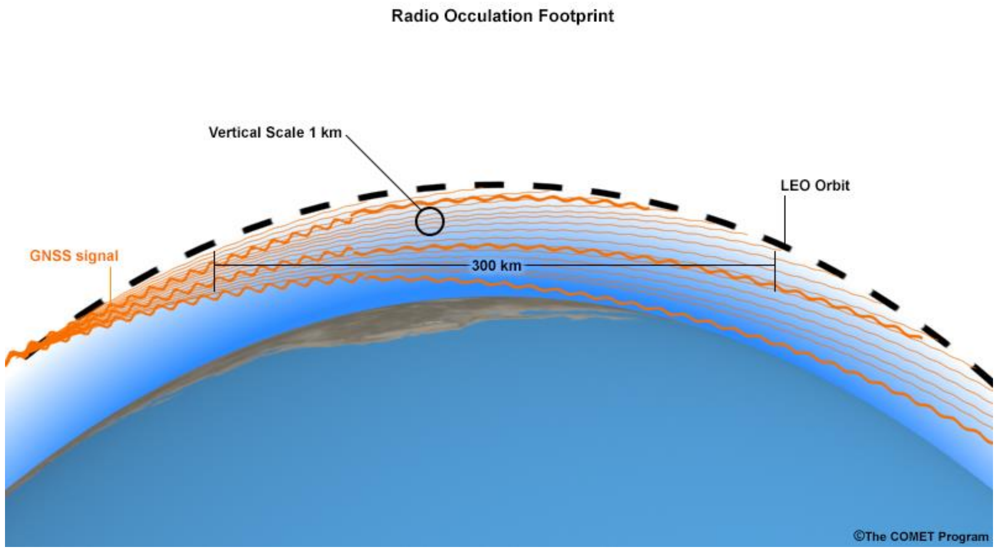


Xinan Yue et al 2014

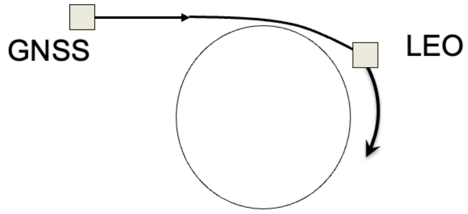
GNSS-RO: Basic idea

As a ray passes through a limb of the atmosphere, the GNSS signal velocity is modified because the refractive index is not unity, **and the path is bent because of gradients in the refractive index**.

GNSS-RO is based on analysing the **bending caused by the neutral atmosphere** along ray paths between a GNSS satellite and a receiver placed on a low-earth-orbiting (LEO) satellite.

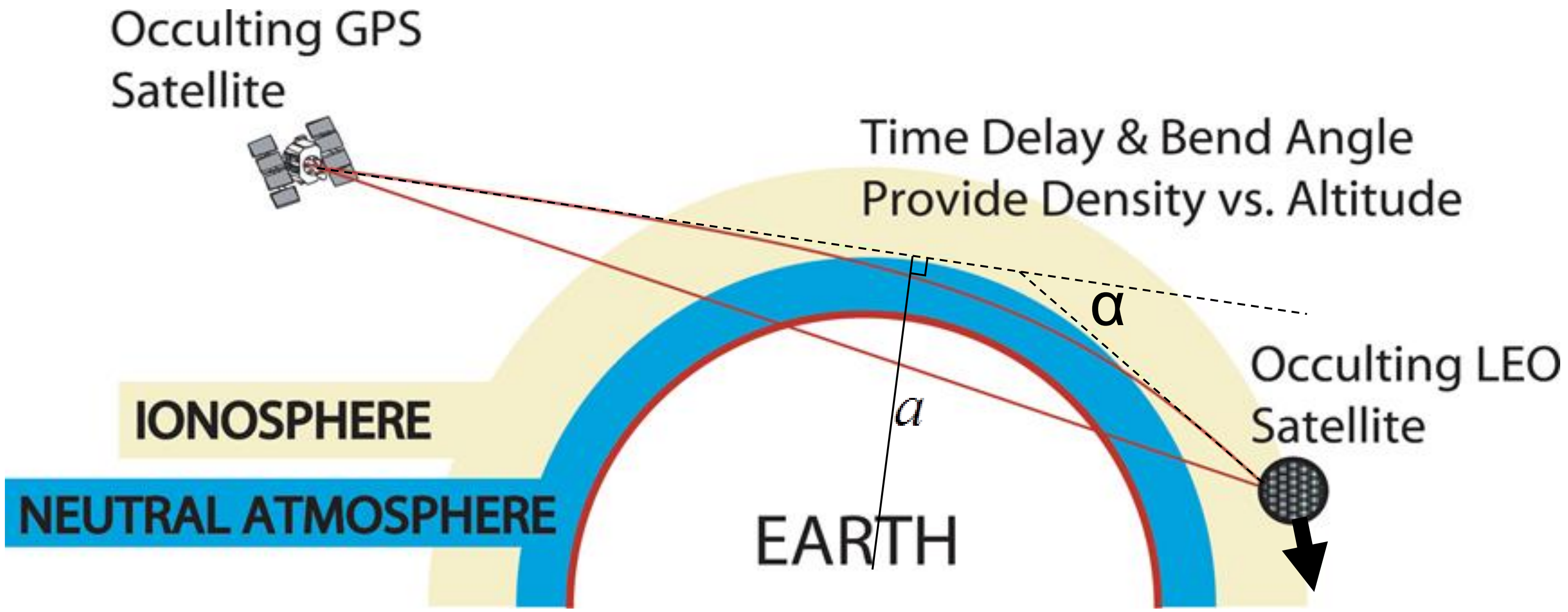


From slide 9….

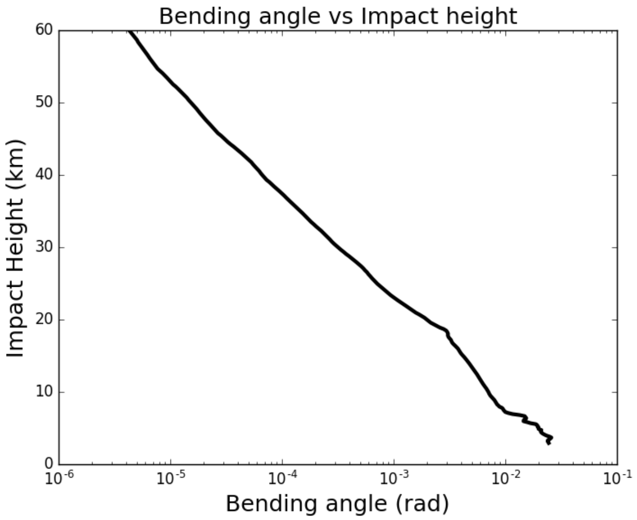


GNSS Receiver placed on satellite in Low Earth Orbit (LEO)

GNSS-RO geometry. “Bending angles”

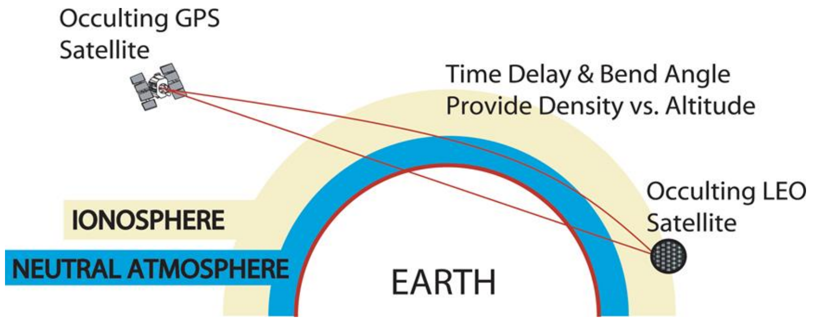


Remember the ship photo!
The LEO tracks the ray as the GNSS satellite sets below the horizon.



<u>Setting occultation</u>: as the LEO moves behind the earth we obtain a **profile** of bending angles, <u>α</u>, as a function of impact parameter, <u>**a**</u>.
The impact parameter is the distance of closest approach for the straight line path.

GNSS-RO characteristics



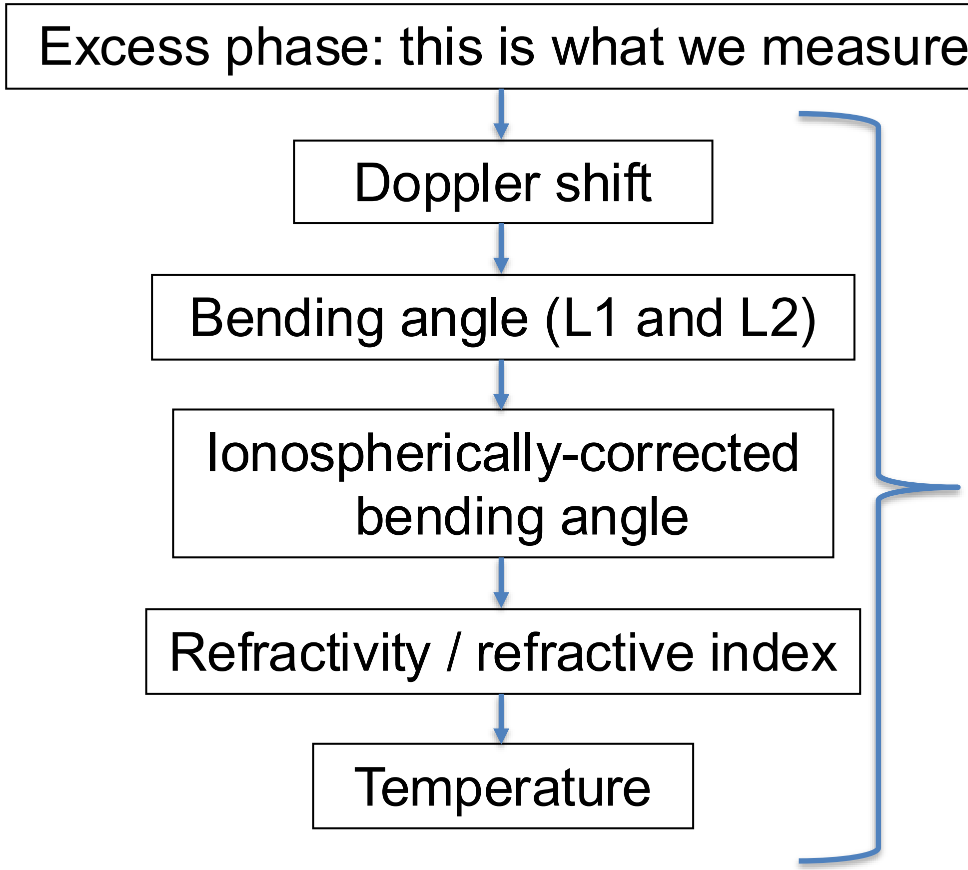
- **Good vertical resolution**: 100m to 1km.
- **Around 70% of the bending occurs over a ~450km section of ray-path**, centred on the tangent point (point closest to surface) – **it has a broad horizontal weighting function, with a ~Gaussian shape to first order!**
- **All weather capability**: not significantly affected by cloud or rain (unlike many radiances).
- Bias-free. It is not a radiometric observation and is tied to atomic clocks.
- The bending is ~1-2 degree near the surface, falling exponentially with height. The scale-height of the decay is approximately the density scale-height (~6-7km).
- A profile of bending angles from ~60km tangent height to the surface takes about 2 minutes. Tangent point drifts in the horizontal by ~200 km during the measurement.

RO processing and retrievals:

How to get *temperature* profiles using the “classical” retrieval.

How to get meaningful information?

Process:



Excess phase: this is what we measure

Doppler shift

Bending angle (L1 and L2)

Ionospherically-corrected bending angle

Refractivity / refractive index

Temperature

Assumptions are required at each step.

Let’s go through these steps.

“Classical retrieval”
1 of 8

Ray Optics Processing of the raw GNSS-RO Observations

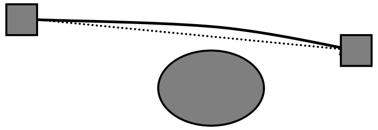
GNSS receivers do not measure temperatures/ray bending directly!

The GNSS receiver on the LEO satellite measures a time series of phase-delays $\phi(i-1)$, $\phi(i)$, $\phi(i+1)$,… at the two GNSS frequencies:

L1 = 1.57542 GHz
L2 = 1.22760 GHz

The phase delays are “**calibrated**” to remove **special and general relativistic effects** and to remove the GNSS and LEO clock errors – calibration is referenced to **atomic clocks**.
(“**Differencing**”, see Hajj et al. (2002), JASTP, **64**, 451 – 469).

We know accurately where the satellites are. Calculate **Excess phase delays**: i.e. remove straight line path delay, $\Delta\phi(i)$.



A time series of **Doppler shifts** at L1 and L2 are calculated by differentiating the **excess phase delays** with respect to time.

“Classical retrieval”
2 of 8

Deriving bending angles from the Doppler shift

The ray bending that is caused by gradients in the atmosphere and

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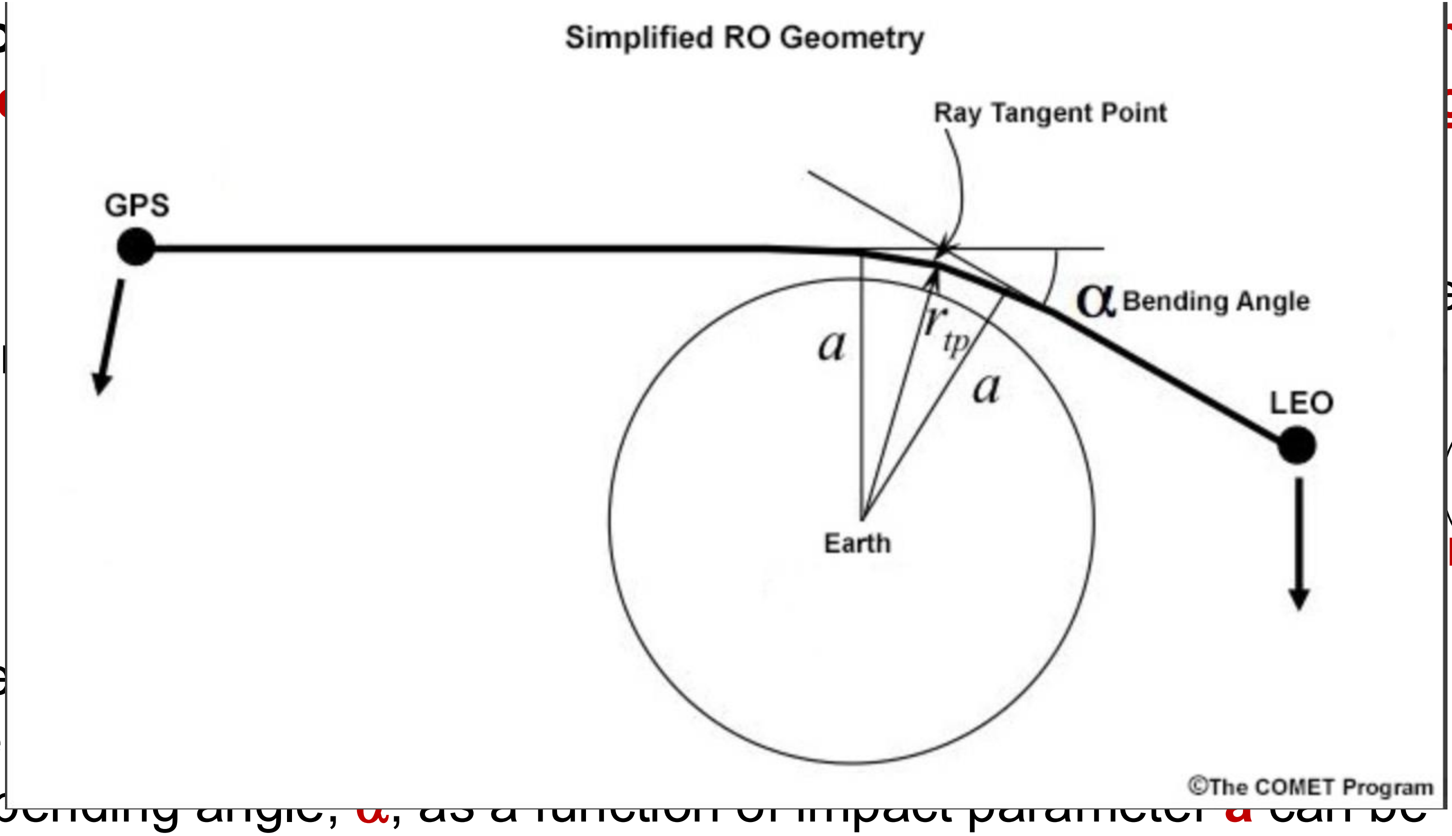

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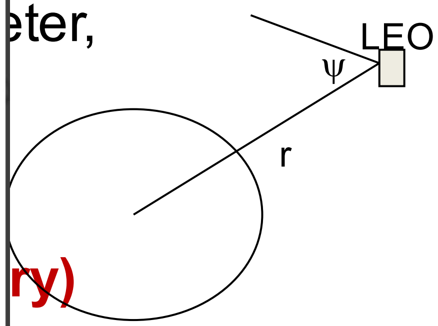

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Give

sate

the bending angle, α, as a function of impact parameter **a** can be derived simultaneously from the Doppler shift.

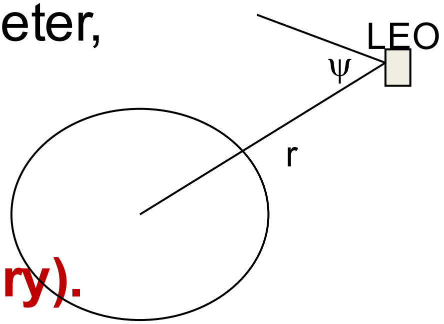
“Classical retrieval”
2 of 8

Deriving bending angles from the Doppler shift

The ray bending that is caused by gradients in the atmosphere and **ionosphere** modify the L1 and L2 Doppler values, but **deriving the bending angles, α, from the Doppler values is an ill-posed problem** **(an infinite set of bending angles could produce the same Doppler)**.

The problem is made well posed by **assuming** the impact parameter, given by

$$\boxed{a = nr\sin\psi}$$

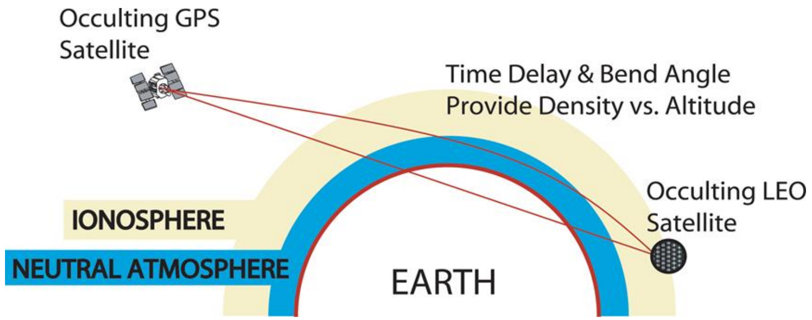


has the same value at both the satellites (=spherical symmetry).

Given accurate position and velocity estimates for the satellites, **and making the impact parameter assumption**, the bending angle, α, as a function of impact parameter **a** can be derived simultaneously from the Doppler shift.

“Classical retrieval”
3 of 8

Removing the effect of the ionosphere



Every ray passes through the ionosphere!

We have to isolate the **atmospheric** component of the bending angle. **The ionosphere is dispersive, but the neutral atmosphere is not** and so we can take a linear combination of the L1 and L2 bending angles to obtain the “corrected” bending angle. See Vorob’ev + Krasil’nikov, (1994), Phys. Atmos. Ocean, **29**, 602-609.

$$\alpha(a) = c\alpha_{L1}(a) - (c-1)\alpha_{L2}(a)$$

$$c = \frac{f_{L1}^2}{\left(f_{L1}^2 - f_{L2}^2\right)}$$

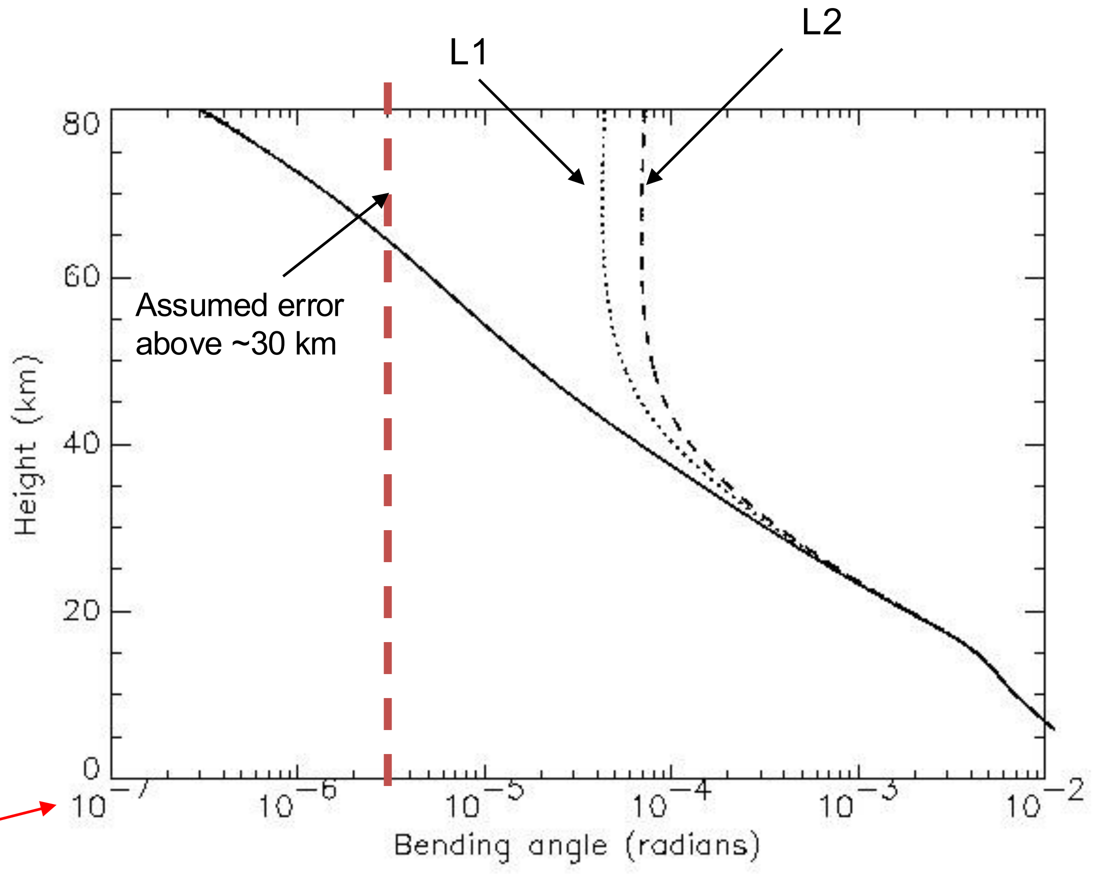
“Corrected” bending angles

Constant given in terms of the L1 and L2 frequencies.

How good is the correction? Does it introduce biases that vary in time with solar cycle?

YES, the retrieved temperatures will be sensitive to this!

The ionospheric correction: a simulated example



Assumed error above ~30 km

Log scale

High up, the ionosphere dominates the L1 and L2 signals, **but they are affected differently to each other**.

Low down, the atmospheric signal dominates and the lines overlap.

The "correction" is very big!

“Classical
retrieval”
5 of 8

Deriving the refractive index profiles

Assuming local **spherical symmetry**, we can use an **Abel transform** to retrieve a refractive index profile

Note the upper-limit of the integral! A priori information needed to extrapolate to infinity.

$$n(x) = \exp\left(\frac{1}{\pi}\int_{x}^{\infty} \frac{\alpha(a)}{\sqrt{a^2 - x^2}}\, da\right)$$

The inverse Abel transform can be used to obtain the bending angle profile for a given refractive index profile (i.e. the inversion).

$$\alpha(a) = -2a\int_{a}^{\infty} \frac{d\ln n / dx}{\sqrt{x^2 - a^2}}\, dx$$

Corrected Bending angle as a function of impact parameter

Convenient variable ($x=nr$)
(refractive index * radius)

“Classical retrieval”
6 of 8

“Statistical optimisation” – needed to calculate refractivity

In order to derive refractivity the **noisy**, **corrected** bending angle profiles must be extrapolated to infinity – **i.e., we have to introduce a-priori simulated bending angles**.

This blending of the observed and simulated bending angles is called “**statistical optimisation**”. Consider the (**matrix**) equation:

$$\boldsymbol{\alpha}_{\mathbf{so}} = \boldsymbol{\alpha}_{\mathbf{m}} + \mathbf{K}\left(\boldsymbol{\alpha} - \boldsymbol{\alpha}_{\mathbf{m}}\right)$$

We use this “blended” profile in the Abel transform to get refractivity!

Model (e.g. MSIS)

“Corrected” BA

It’s a linear combination of simulated bending angles from a climatology model (e.g., MSIS)

The gain matrix, **K**, determines the relative contribution of the model. **By ~60 km the merged profile is dominated by the model contribution.**

“Classical retrieval”
7 of 8

Determining profiles of density (dry atmosphere only)

The refractive index (or refractivity) is related to the pressure, temperature and vapour pressure using two experimentally-determined constants (from the 1950s and 1960s!)

N= refractivity
n= refractive index
c1,c2 refractivity constants
P= pressure
T= Temperature
Pw= partial pressure of water vapour
ρ= density
R= gas constant

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

$$= \frac{c_1 P}{T} + \frac{c_2 P_w}{T^2}$$

This two-term expression is probably the simplest formulation for refractivity, but it is widely used in GNSS-RO.

We now use an alternative three term formulation, including non-ideal gas effects

If the water vapour is negligible, the 2nd term = 0, and the refractivity is proportional to the density

$$N \approx \frac{c_1 P}{T} = c_1 R \rho$$

So, although we don’t know the values of P and T, we can use the ideal gas equation to retrieve a vertical profile of density!

“Classical retrieval”
8 of 8

Final step!: “Dry temperature” retrieval

We need to estimate the temperature on a pressure level to integrate the hydrostatic equation

$$P(z) = \underset{\text{a priori}}{P(z_u)} - \frac{1}{c_1 R}\int_{Z}^{z_u} N(z) g(z) dz$$

Overall, I would be sceptical about GNSS-RO temperature retrievals above ~5 hPa. **Be aware that the temperature will be very sensitive to the a priori.**

Then, the “dry temperature” can be calculated:

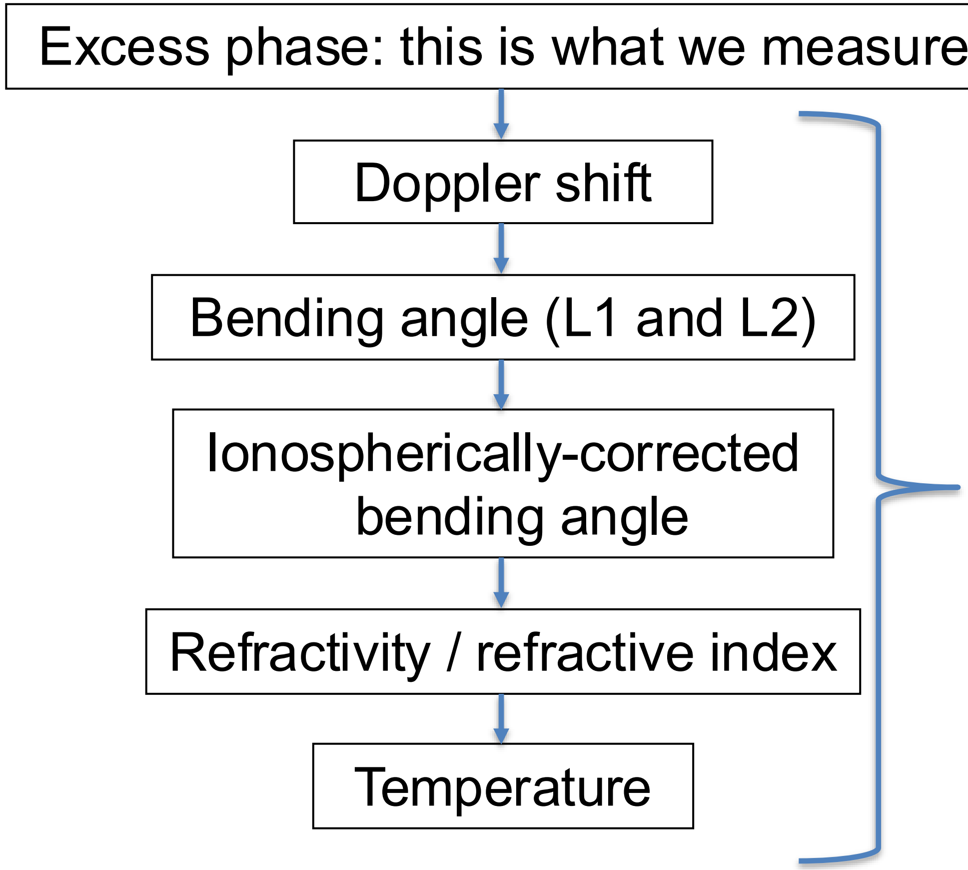
$$T(z) = c_1 \frac{P(z)}{N(z)}$$

High up, the a priori strongly affects the retrieval. Low down, any water vapour will affect the accuracy.

GPS/MET experiment (1996): Groups from JPL and UCAR demonstrated that the retrievals agreed with co-located analyses and radiosondes to within 1K between ~5-25km. e.g., See Rocken et al, 1997, JGR, 102, D25, 29849-29866.

Summary

Process:



Excess phase: this is what we measure

Doppler shift

Bending angle (L1 and L2)

Ionospherically-corrected bending angle

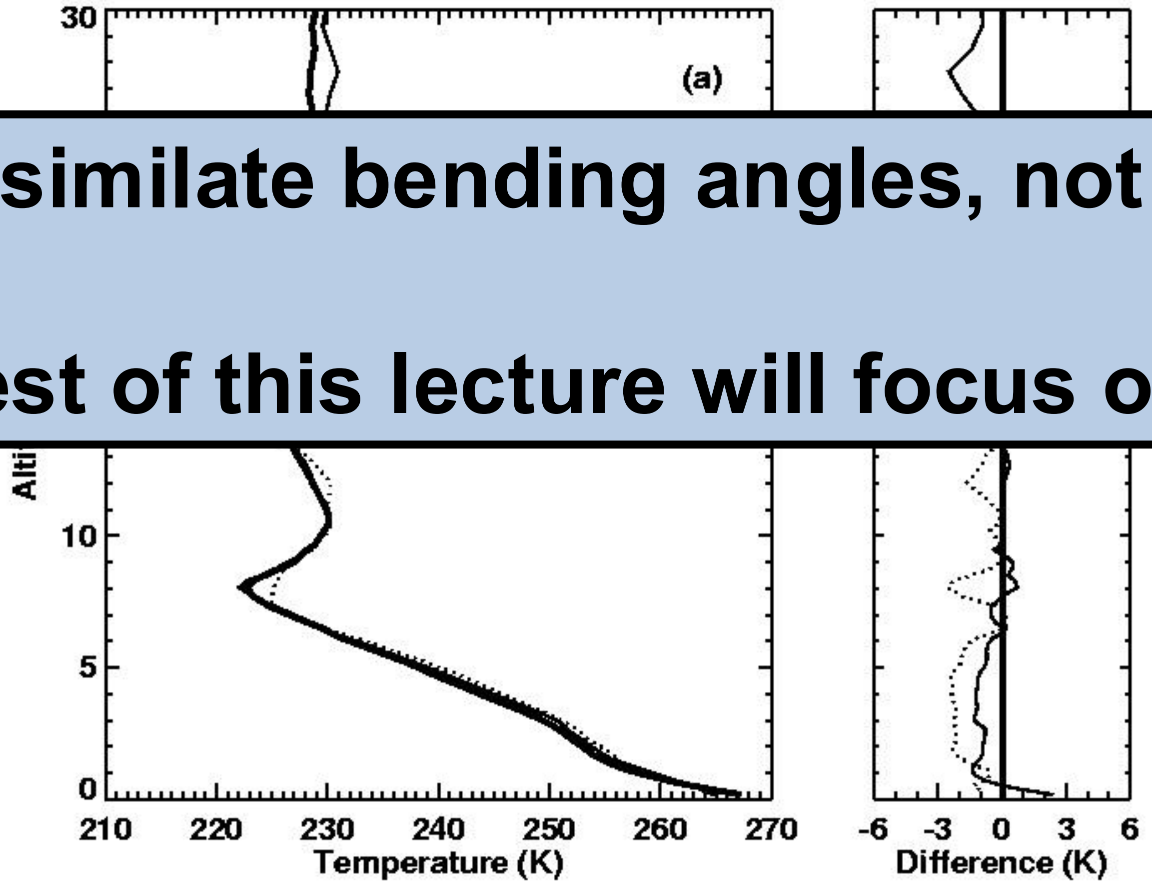
Refractivity / refractive index

Temperature

Assumptions are required at each step.

GPS/MET Temperature Sounding

(Kursinski et al, 1996, Science, 271, 1107-1110, Fig2a)



We assimilate bending angles, not temperature retrievals.

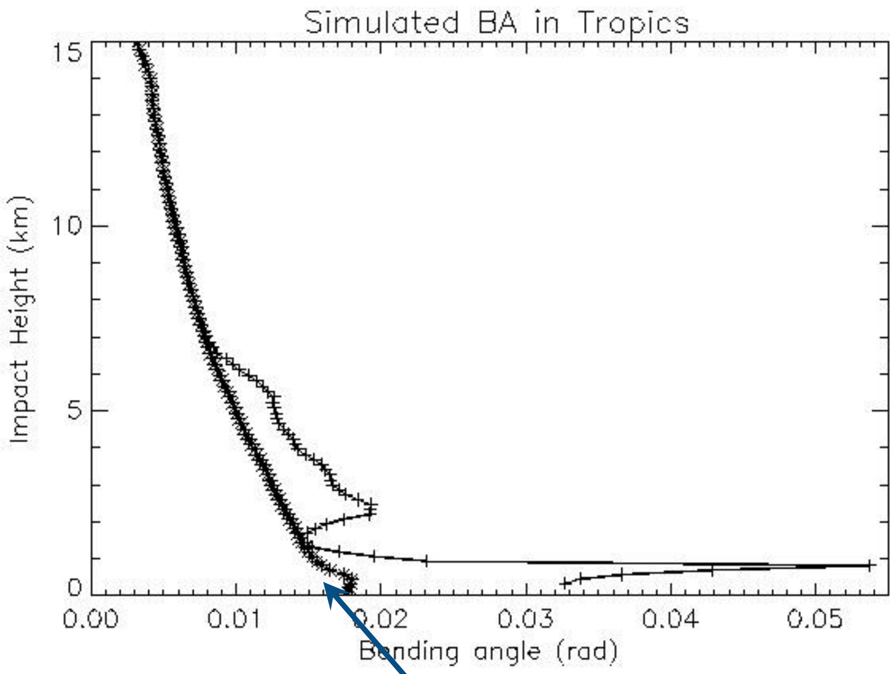
The rest of this lecture will focus on bending angles.

and UCAR in mid 1990s got the subject moving.

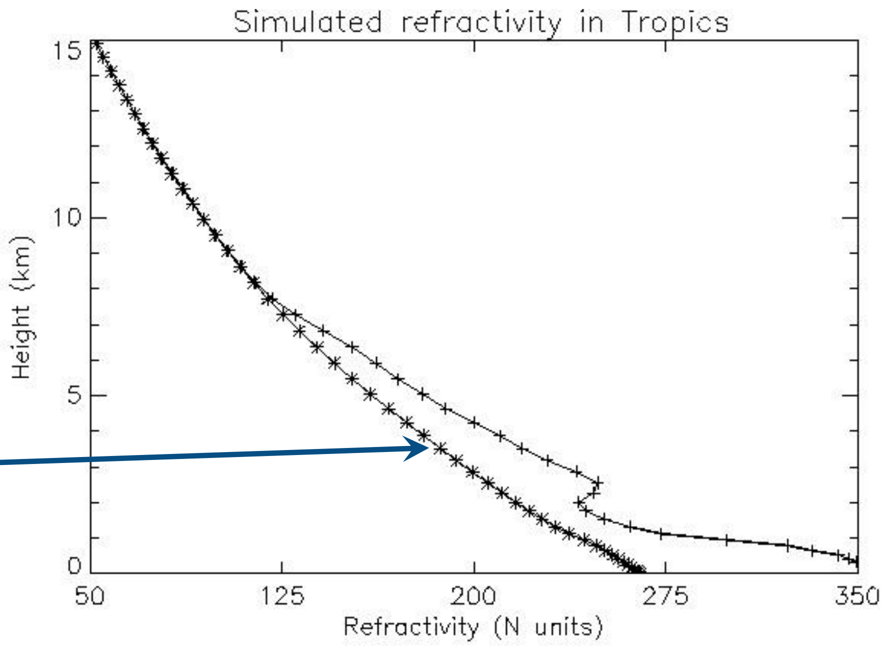
(Location 69N, 83W.
01.33 UT, 5th May, 1995)

Some complexities(!)

Outside the core-region
Troposphere: we can’t neglect water vapour



Difference between the lines show the impact of water vapour.

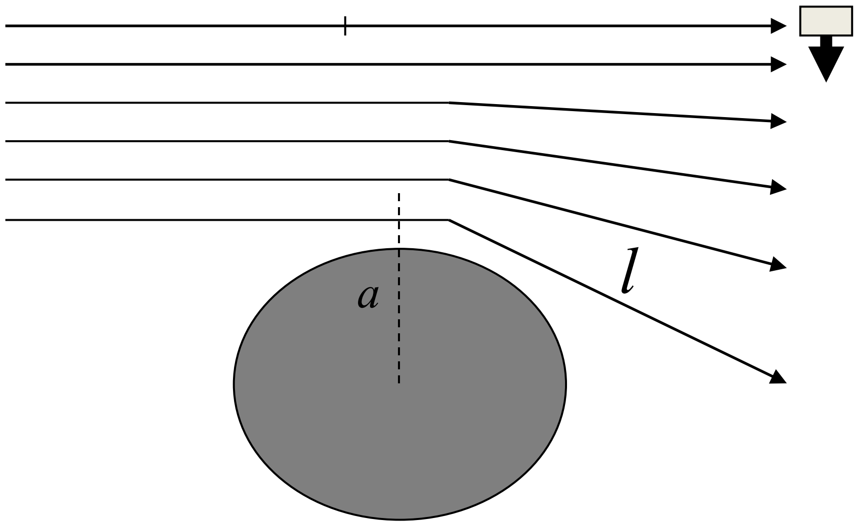


Simulated ignoring water vapour.

We need a *variational* system to reliably retrieve water vapour information.

Physical limitations in the lower troposphere

Atmospheric defocusing: If the bending angle changes rapidly with height, the signal reaching the receiver has less power



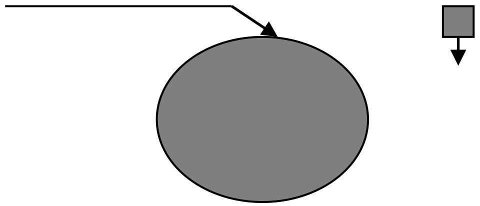
A tube of rays is spread out by the ray bending and the **signal to noise falls**.

$$\boxed{DF \propto \frac{1}{1-l\left(\frac{\partial \alpha}{\partial a}\right)}}$$

Atmospheric ducting: if the refractive index gradient exceeds a critical value the signal is lost as the ray does not emerge.

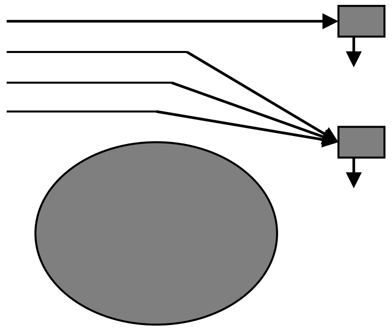
Not affected by clouds? **But we often get ducting conditions near the top of stratocumulus clouds**

$$-\,{}^{dn}\!/_{dr} \geq {}^{1}\!/_{R_e}$$



Limitations – lower troposphere

•**Atmospheric Multipath** processing – more than one ray is measured by the receiver at a given time:



Single ray region – geometric ray optics approach ok!

Multipath: More than one ray arrives at the receiver. They interfere.

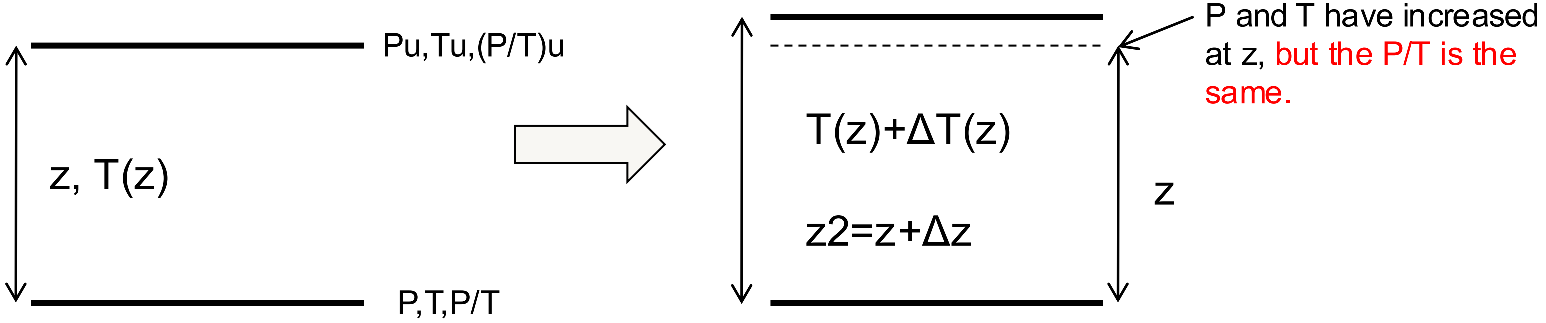
•**The amplitude of the signal can fluctuate rapidly.**

•**Wave optics retrievals –** these are elegant co-ordinate transforms. Without these, we would not be able to make good use of GNSS-RO in the troposphere. **(These still assume spherical symmetry)**: e.g, Full Spectral Inversion. Jensen et al 2003, Rad. Sci., **38**, 10.1029/2002RS002763. **Canonical transforms, Gorbunov and Lauritsen, 2004, Rad. Sci., 39, RS4010, doi:10.1029/2003RS002971**

•**Improved GNSS receiver software:** Open-loop processing.

GNSS-RO also has a “null space”

The measurement is related to density (~P/T) on height levels and this ambiguity means that the effect of some temperature perturbations **can’t be measured**. Assume two levels separated by z, with temperature variation T(z) between them. Now add positive perturbation ΔT(z)~exp(z/H), where H is the density scale height



Pu,Tu,(P/T)u

z, T(z)

P,T,P/T

P and T have increased at z, but the P/T is the same.

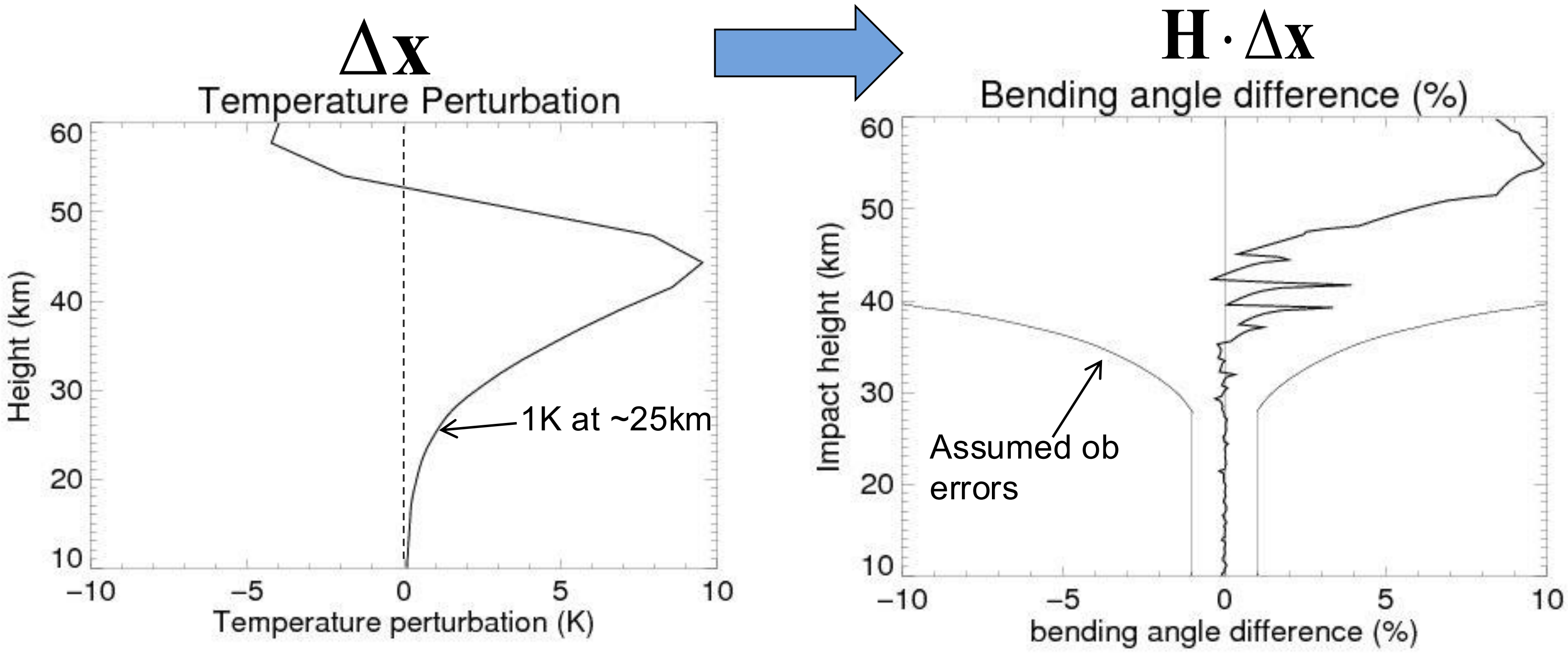
T(z)+ΔT(z)

z2=z+Δz

z

The density as a function of height is almost unchanged. **A priori information required to distinguish between these temperature profiles.** **This is the GNSS-RO null space.**

Null space – how does a temperature perturbation propagate through the bending angle observation operator?



The null space arises because the measurements are sensitive to density as function of height (~P(z)/T(z)). A priori information is required to split this into T(z) and P(z). We can define a temperature perturbation ΔT(z)~exp(z/H) which is in the GNSS-RO null space. Therefore, if the model background contains a bias of this form, the measurement can't see or correct it.

Assimilation of GNSS-RO data:

What observations are available?

How do we use them?

Pros and cons.

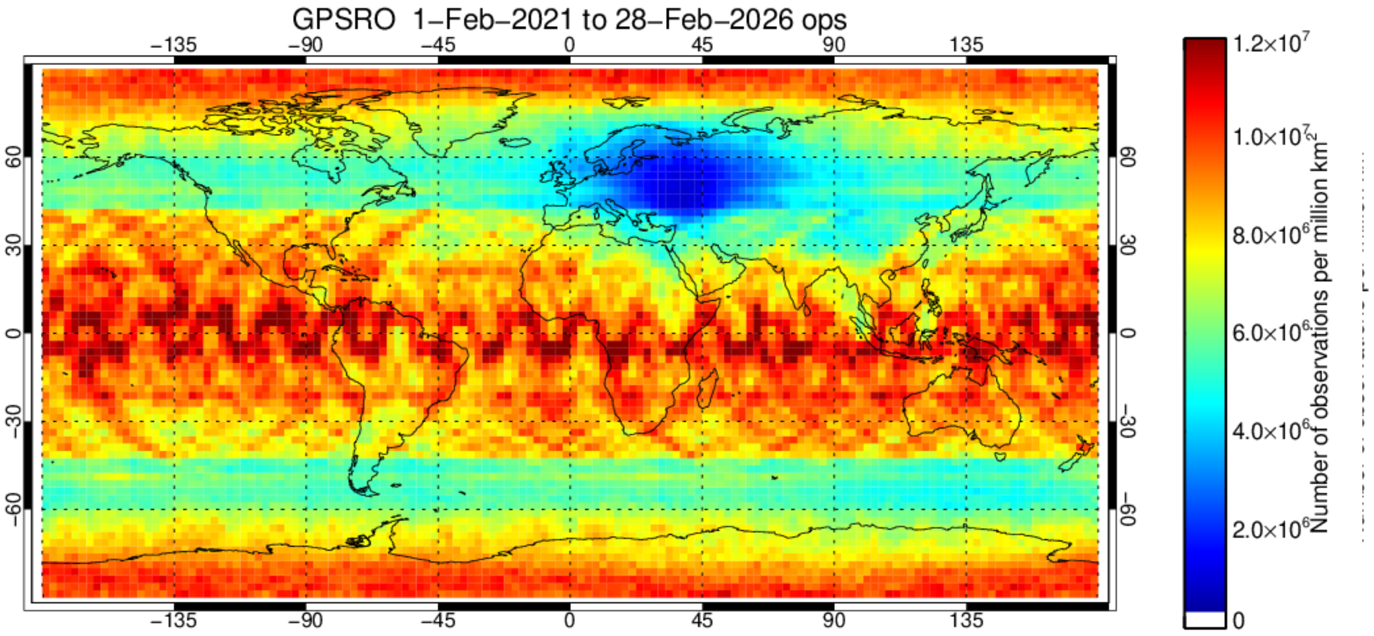
Data availability

- Current status: ~**18.000** profiles per day:
  - Missions of opportunity: **TerraSAR-X and Tandem-X**. (~240 and 75 profiles per day)
  - The **GRAS** instruments on the EUMETSAT satellites Metop-B and Metop-C provides 2 x ~550 profiles per day, also **GRAS-2** from Metop-D provides ~1400 profiles per day (**assimilated since 11th March 2026)**
  - **Sentinel 6A** (~650 profiles per day)
  - The **GNOS** instrument on the Chinese satellite FY-3D are currently being monitored, **GNOS-2** from FY-3E is assimilated since July 2025
  - **KOMPSAT-5** is being assimilated. (~100 profiles per day, at the moment no data)
  - **COSMIC-2** is an **operational** tropical constellation of 6 satellites (obs limited to latitudes ~40S to ~40N). and has been assimilated since March 2020. **GLONASS** signals are used as well as GPS. (~6000 profiles per day)
  - **GRACE C** (monitoring of GRACE D) (~100 profiles per day)
  - Commercial data by **Spire** (~4500 profiles per day) and by **PlanetiQ** (~7000 profiles per day)
- Near future
  - **PAZ** – a Spanish mission with a unique polarimetric (precipitation) capability. We started developing a forward operator to test the assimilation of this polarimetric data.
  - Other commercial companies (Yunyao, Tianmu, (GeoOptics)…) have also launched satellites with RO instrument.
  - Metop-SG-B1 and Sentinel 6B

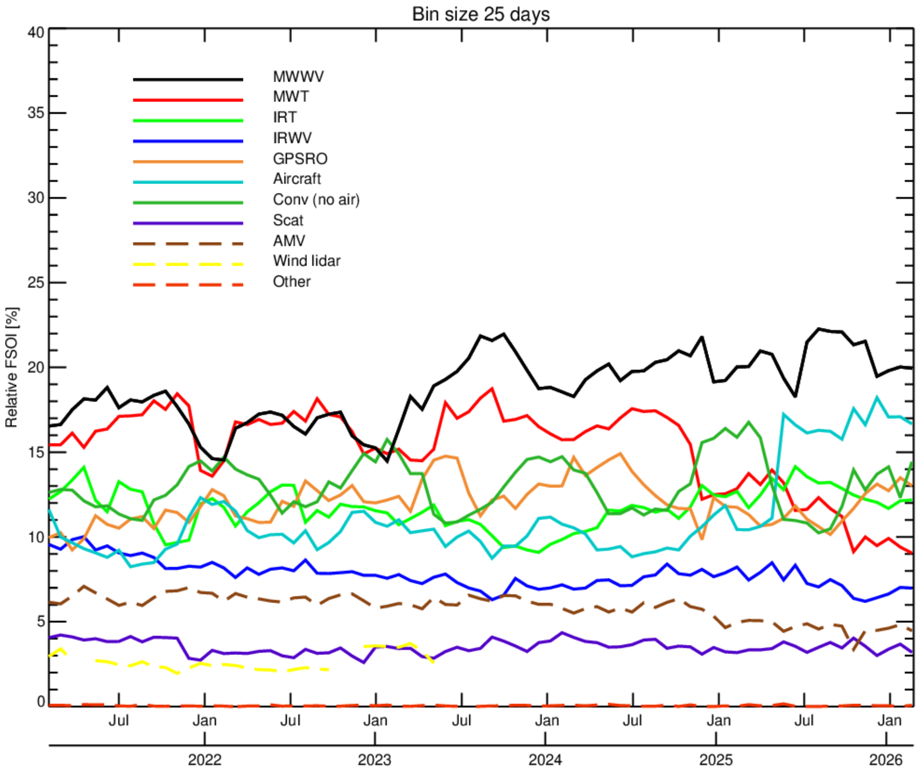
Data coverage and impact of GNSS-RO data

- Changes in GNSS-RO data volume reflect on FSOI
- Number of GNSS RO observations varies across the globe

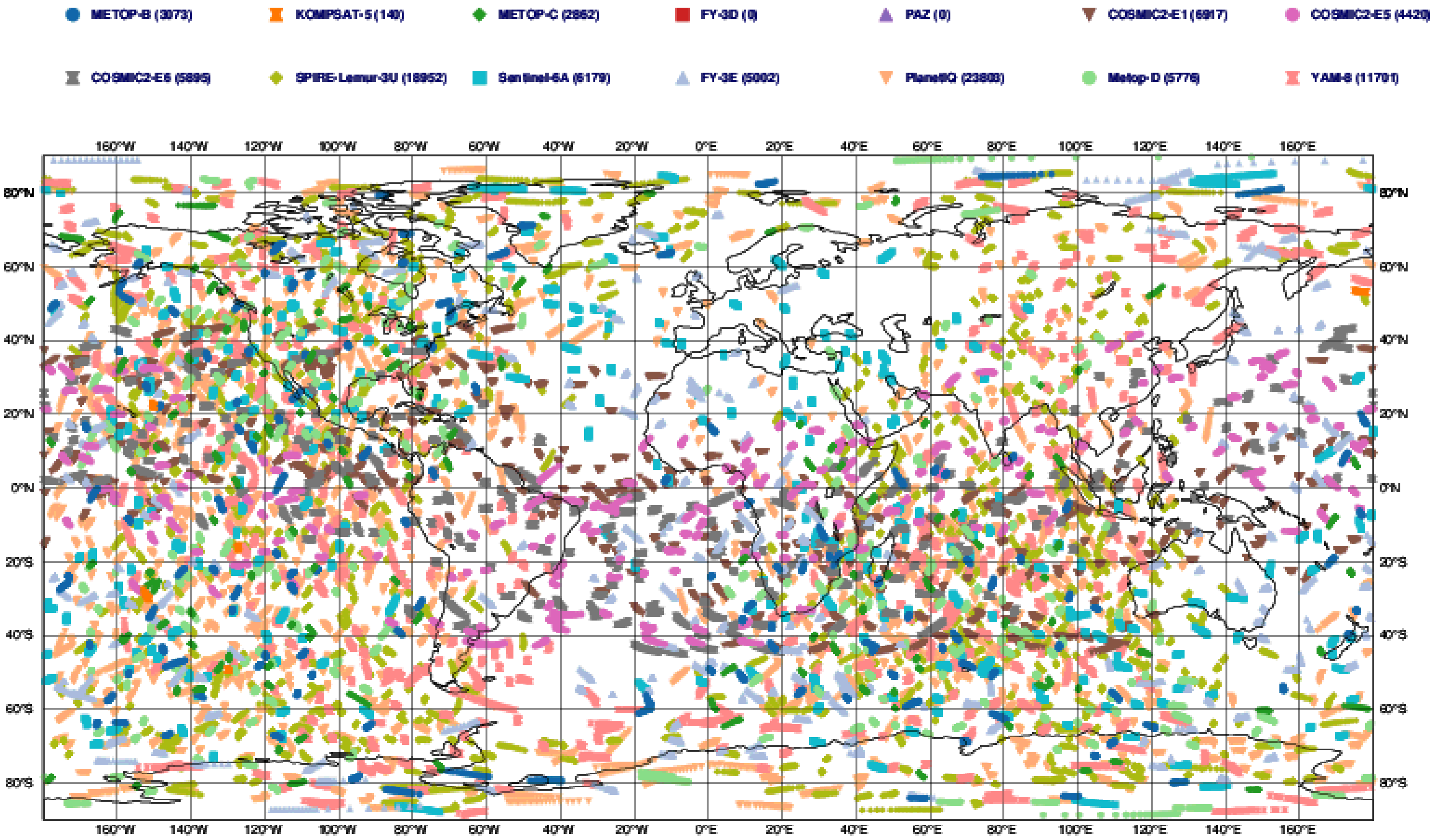
Global coverage



Relative forecast impact (FSOI).
GNSS-RO is orange



ECMWF data coverage (used observations) - GPSRO
2026032315 to 2026032321
Total number of obs = 94720



Why are GNSS-RO observations useful for NWP given that we already have millions of radiance measurements?

GNSS-RO complements the radiances!

Observations are useful if they provide **new** information.

1) RO can be assimilated **without bias correction**. The observations are good for highlighting model errors/biases. Most satellite radiance observations require bias correction to the model. GNSS-RO measurements ***anchor* the bias correction of radiance measurements**.

Importance of anchor measurements in weak constraint 4D-Var. (Climate/reanalysis applications). More on this in the next lecture.

2) GNSS-RO (limb sounders in general) have **sharper weighting functions in the vertical** compared to radiances and therefore have good vertical resolution properties. The GNSS-RO measurements can "see" vertical structures that are in the **"null space"** of the satellite radiances.

1D forward model (="observation operator")
Going from model variables to observed quantities

Assume that a **single model column** represents the state of the entire portion of atmosphere traversed by the ray.

First, calculate the refractivity on model levels:

$$N(x) = \frac{c_1 P(x)}{T(x)} + \frac{c_2 P_w(x)}{T(x)^2}$$

Convert to refractive index:

$$n(x) = 1 + 10^{-6} N(x)$$

Use Abel transform to calculate bending angle (assuming ~exponential variation of N(x) between model levels):

$$\alpha(a) = -2a \int_a^\infty \frac{d\ln n \big/ dx}{\sqrt{x^2 - a^2}}\, dx$$

← I.e. we simulate the bending angles from the model fields.

See Healy & Thépaut, 2006 for more details of how to compute this integral.

1D-Var retrieval

The 1D-Var retrieval minimises the cost function (**x** means model state vector here!):

$$J(\mathbf{x}) = \frac{1}{2}\left(\mathbf{x}-\mathbf{x}_b\right)^T \mathbf{B}^{-1}\left(\mathbf{x}-\mathbf{x}_b\right) + \frac{1}{2}\left(\mathbf{y}_m - H\left(\mathbf{x}\right)\right)^T \mathbf{R}^{-1}\left(\mathbf{y}_m - H\left(\mathbf{x}\right)\right)$$

The **observation operator** - simulating **bending angles** or **refractivity** from the forecast state.

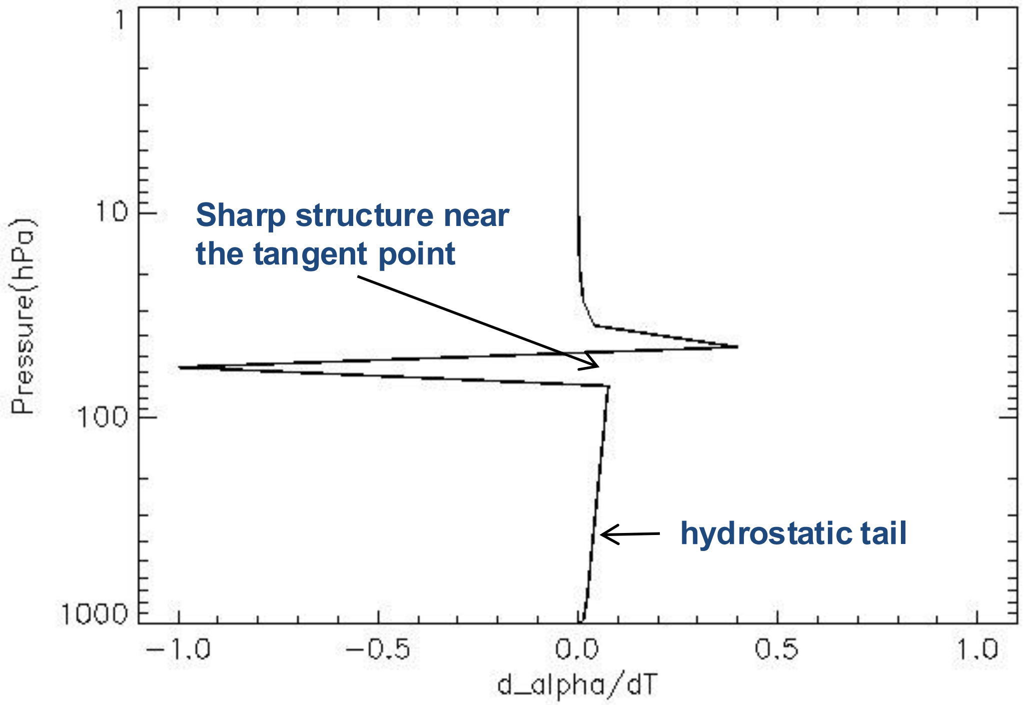
The 1D-Var approach provides a framework for testing observation operators that we might use in 3D/4D-Var assimilation.

The information is partitioned between increments in temperature, humidity and surface pressure, according to their relative uncertainties.

We can also investigate various **information content** measures.

1D bending angle Jacobian (weighting function) for temperature

(Normalised with the peak value)



Sharp structure near the tangent point

hydrostatic tail

(See also Eyre, ECMWF Tech Memo 199, 1994)

$$\left(\frac{\partial\alpha}{\partial T}\right)$$

Weighting function peaks at the pressure levels above and below the ray tangent point. Bending related to **vertical gradient of refractivity**:

$$N = {c_1 P}/{T}$$

$$\Delta\alpha \propto (N_l - N_u)$$

Increase the T on the **lower level** – reduce the N gradient – less bending!

Increase the T on the **upper level** – increase N gradient more bending!

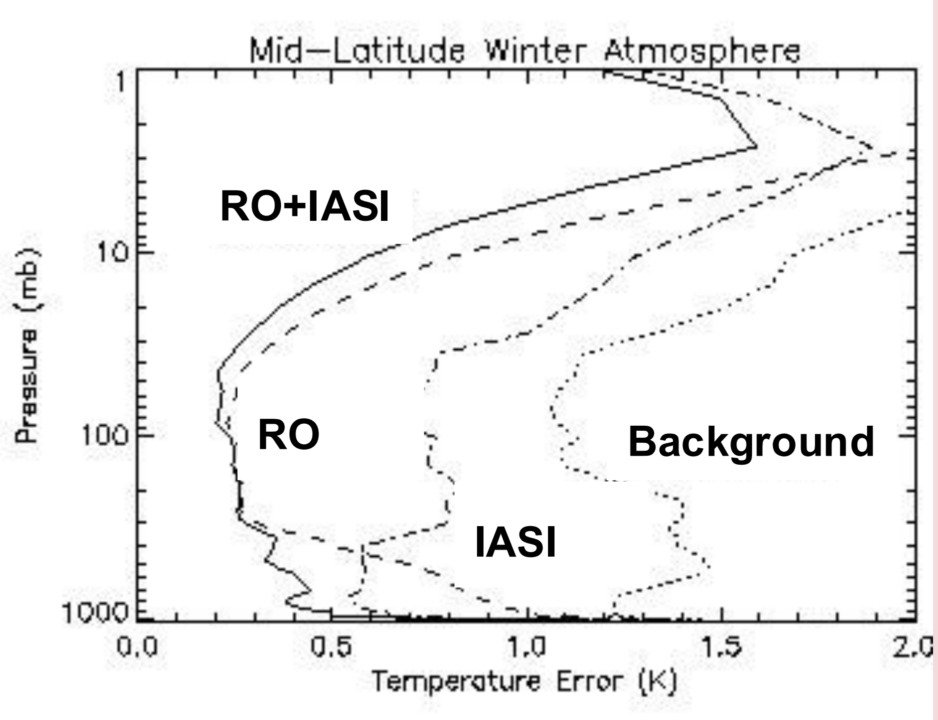
Very sharp weighting function in the vertical – we can resolve structures that nadir sounders cannot!

The refractivity Jacobian is even sharper, but vertical correlations are larger.

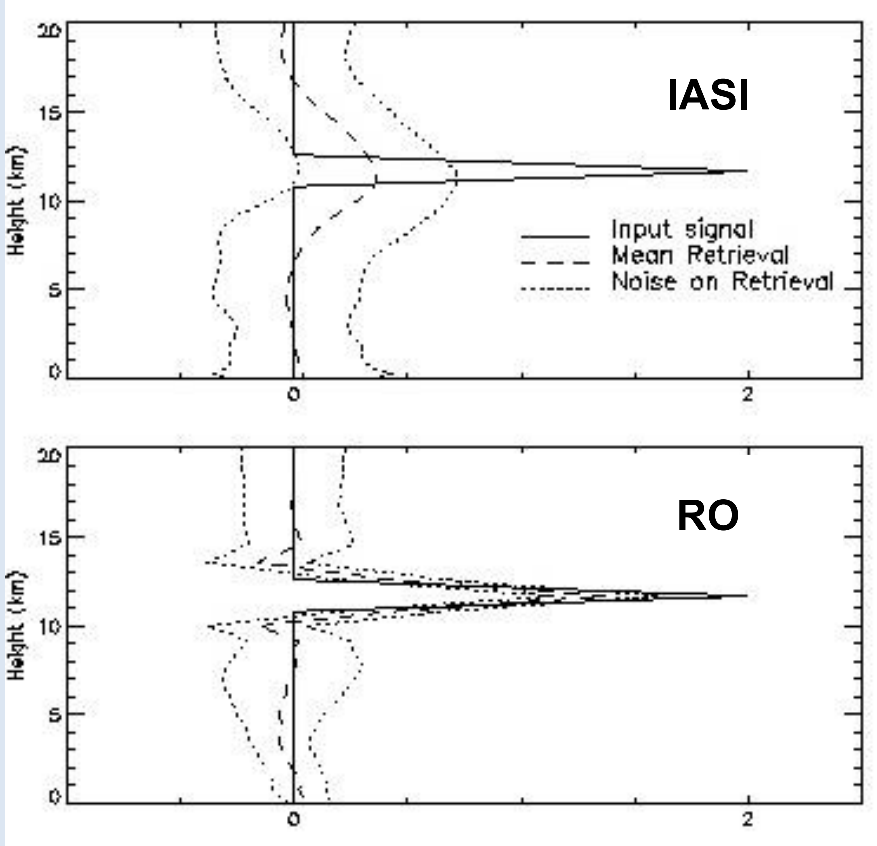
GNSS-RO and IASI: 1D-Var simulations

Healy and Collard 2003, QJRMS:

Expected retrieval error:



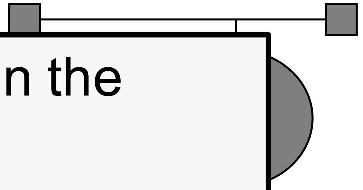
Power to resolve a peak-shaped error in background: Averaging Kernel.



Co-located RO and IASI observations are assimilated in a 1D-Var.

1D bending angle assimilation at Met Office, NCEP, MF, ECMWF (until 2014)

- **Most centres assimilate bending angles with a 1D operator**: ignore the 2D nature of the measurement and use a **single model column** to integrate

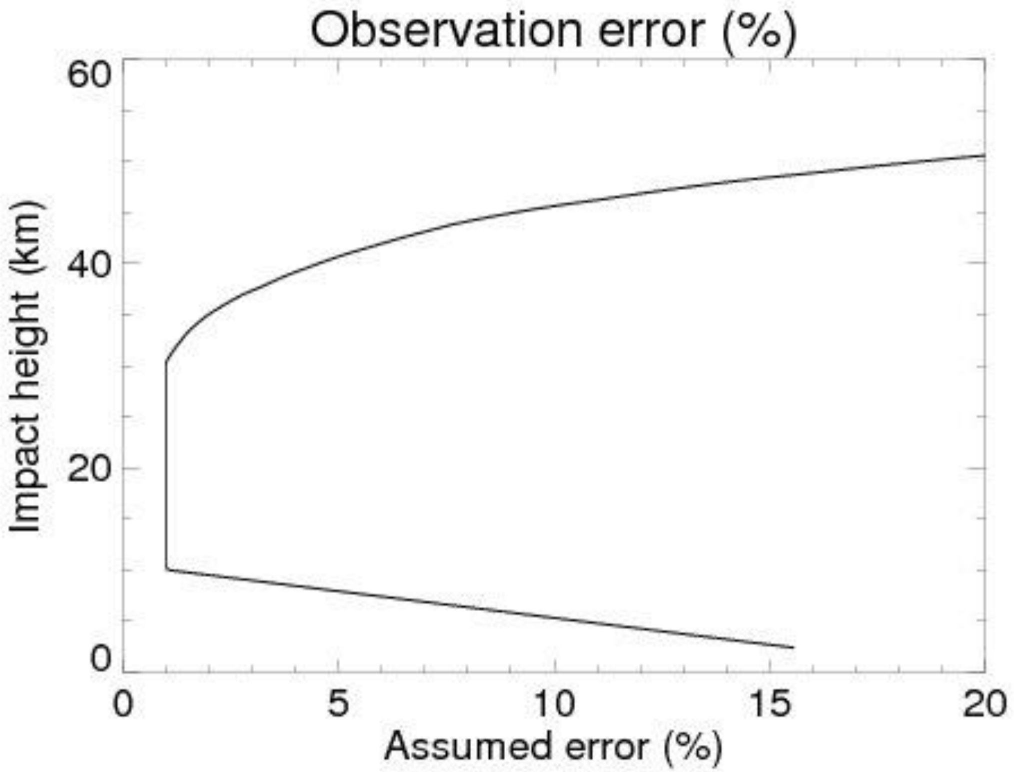


Note the dependence on geopotential height and Q in the forward model!

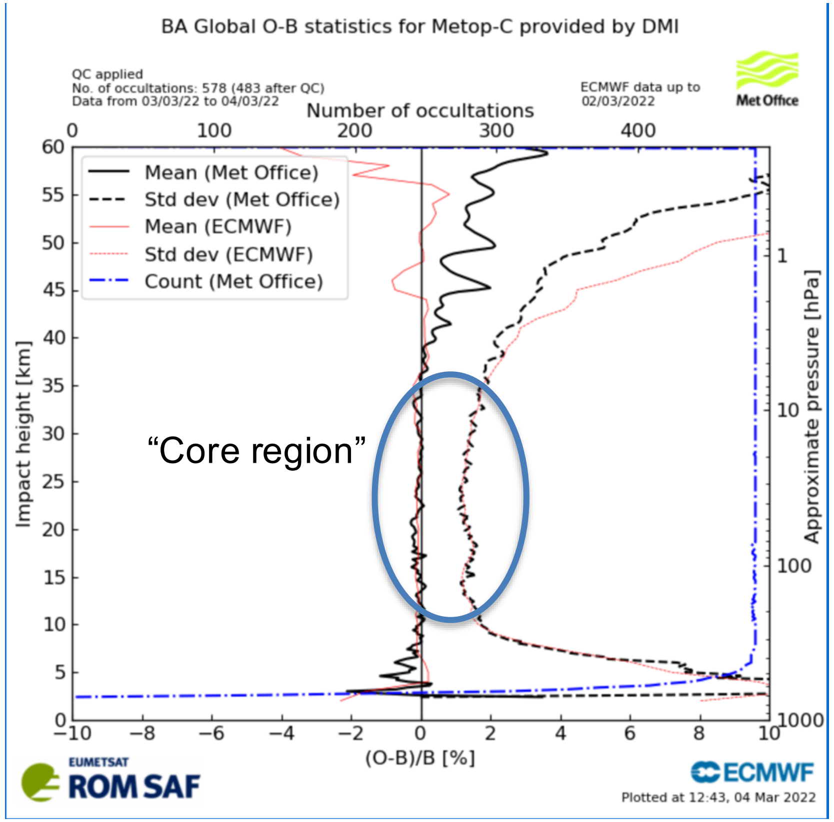
In principle, GNSS-RO provides surface pressure and tropospheric humidity information to the analysis via the adjoint of the forward model.

- The
  - convert geopotential height to geometric height and radius values
  - evaluate the refractivity, N, on model levels **from P,T and Q**.
  - Integrate, assuming refractivity varies ~(*exponentially*quadratic*) between model levels. (*Solution in terms of the Gaussian error function*).
  - **Include tangent point drift (May 2011).**
  - **2D operator operational at ECMWF since 2014 (later in talk).**

Assumed global observation (BA) errors and actual (o-b) departure statistics

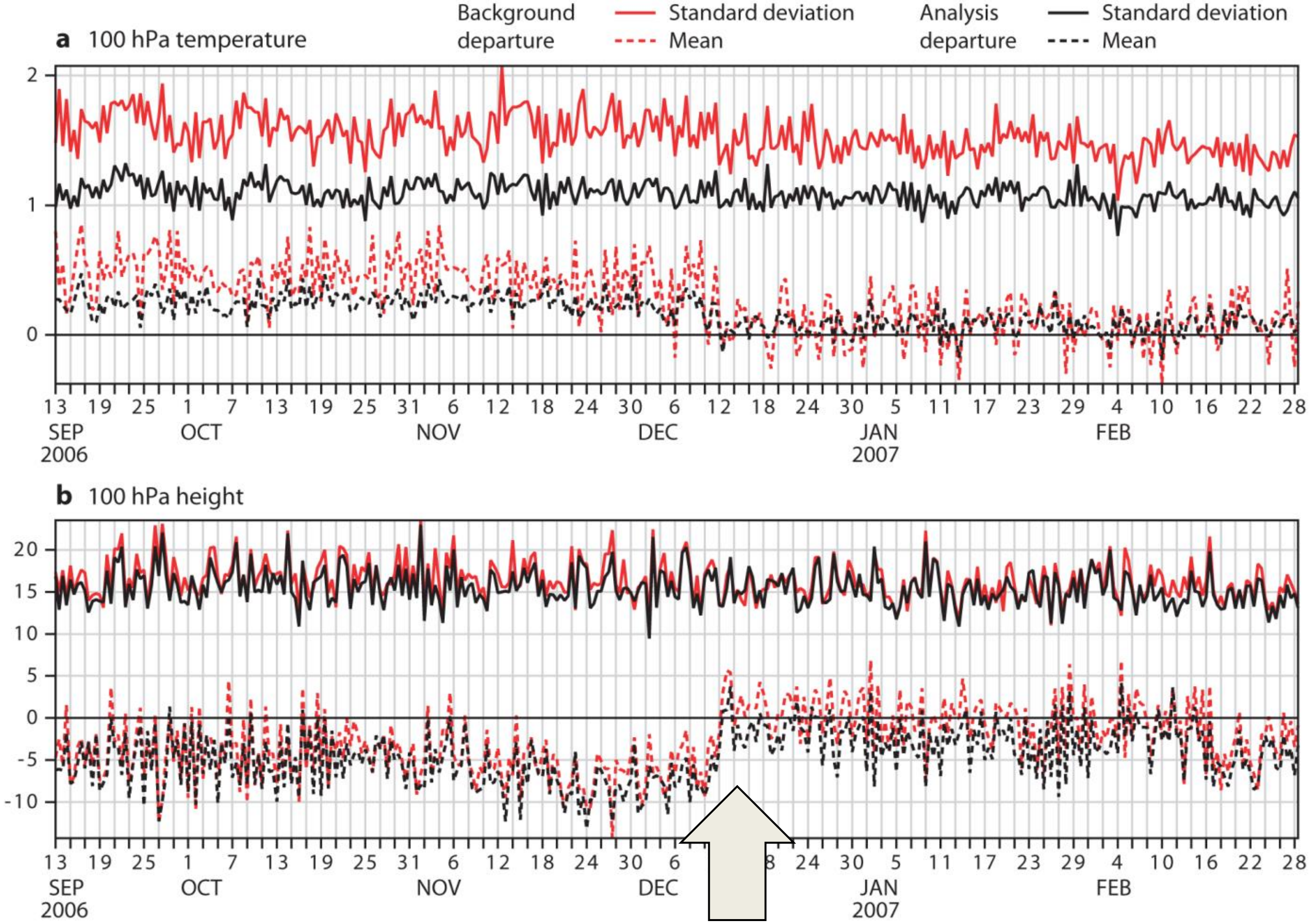


Consistent with o-b stats.



See **http://www.romsaf.org/monitoring/** for many plots of real-time RO statistics.

Impact of GNSS-RO on ECMWF operational biases against radiosonde measurements



Operational implementation (COSMIC 1-6 and CHAMP)

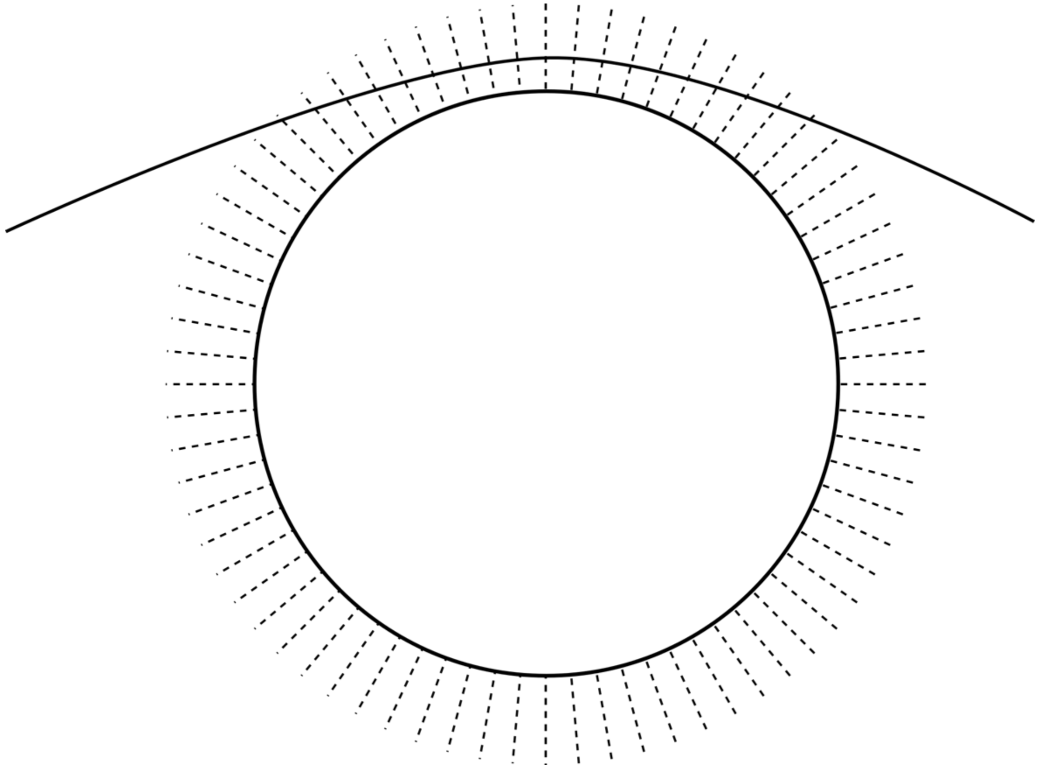
2D forward models:

Using model information from multiple model columns.

Tracing rays through the model atmosphere

- It has been suggested that the use of 1D operators is limiting the GNSS-RO impact in the troposphere.
- 1D operators assume that the entire limb of the atmosphere being sampled can be represented by a single column – a big assumption.
- ECMWF now assimilates GNSS-RO with a 2D operator.
- This complicates the forward model (and, more so, the adjoint!).

In a 2D operator, multiple model columns are used, instead of assuming that the nearest column to the tangent point represents the entire portion of atmosphere traversed by the ray.



Assimilation with a 2D observation operator

1D:

$$\alpha(a) = -2a\int_a^\infty \frac{d\ln n/dx}{\sqrt{x^2-a^2}}\,dx$$

Integrate these differential equations to determine the ray path:

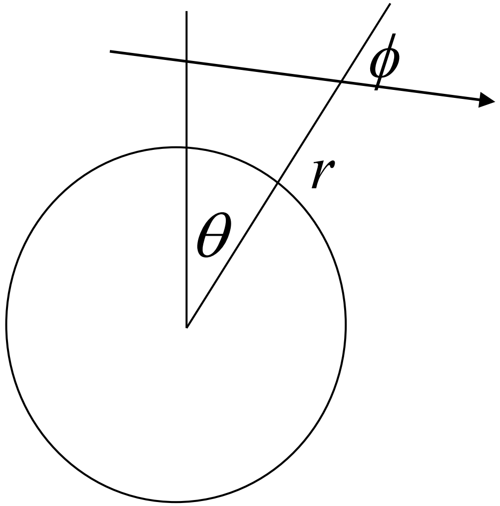
$$\frac{dr}{ds} = \cos\phi$$

$$\frac{d\theta}{ds} = \frac{\sin\phi}{r}$$

$$\frac{d\phi}{ds} \approx -\sin\phi\left[\frac{1}{r} + \left(\frac{\partial n}{\partial r}\right)_\theta\right]$$

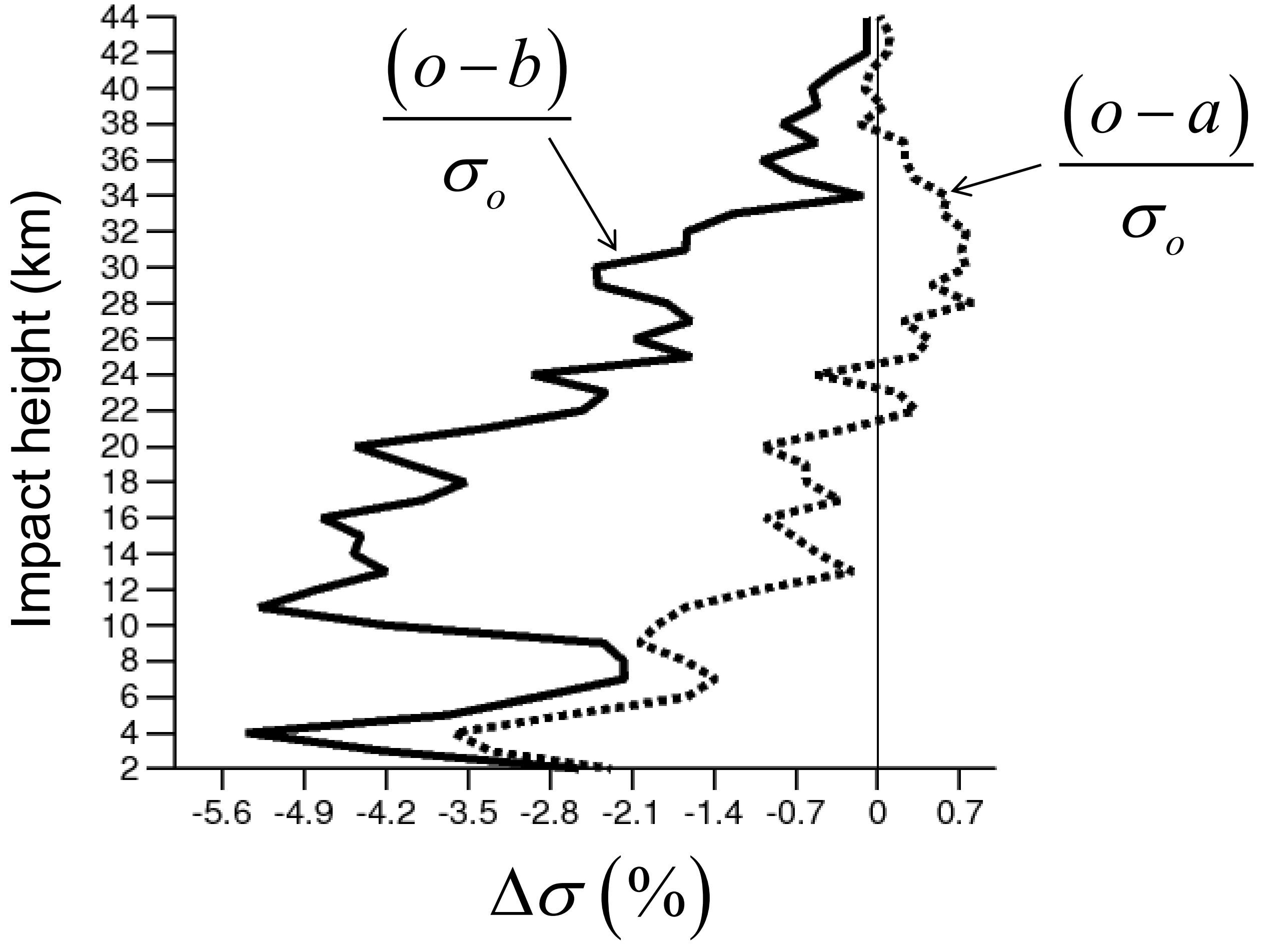
Rodgers, page 149

s= distance along ray path



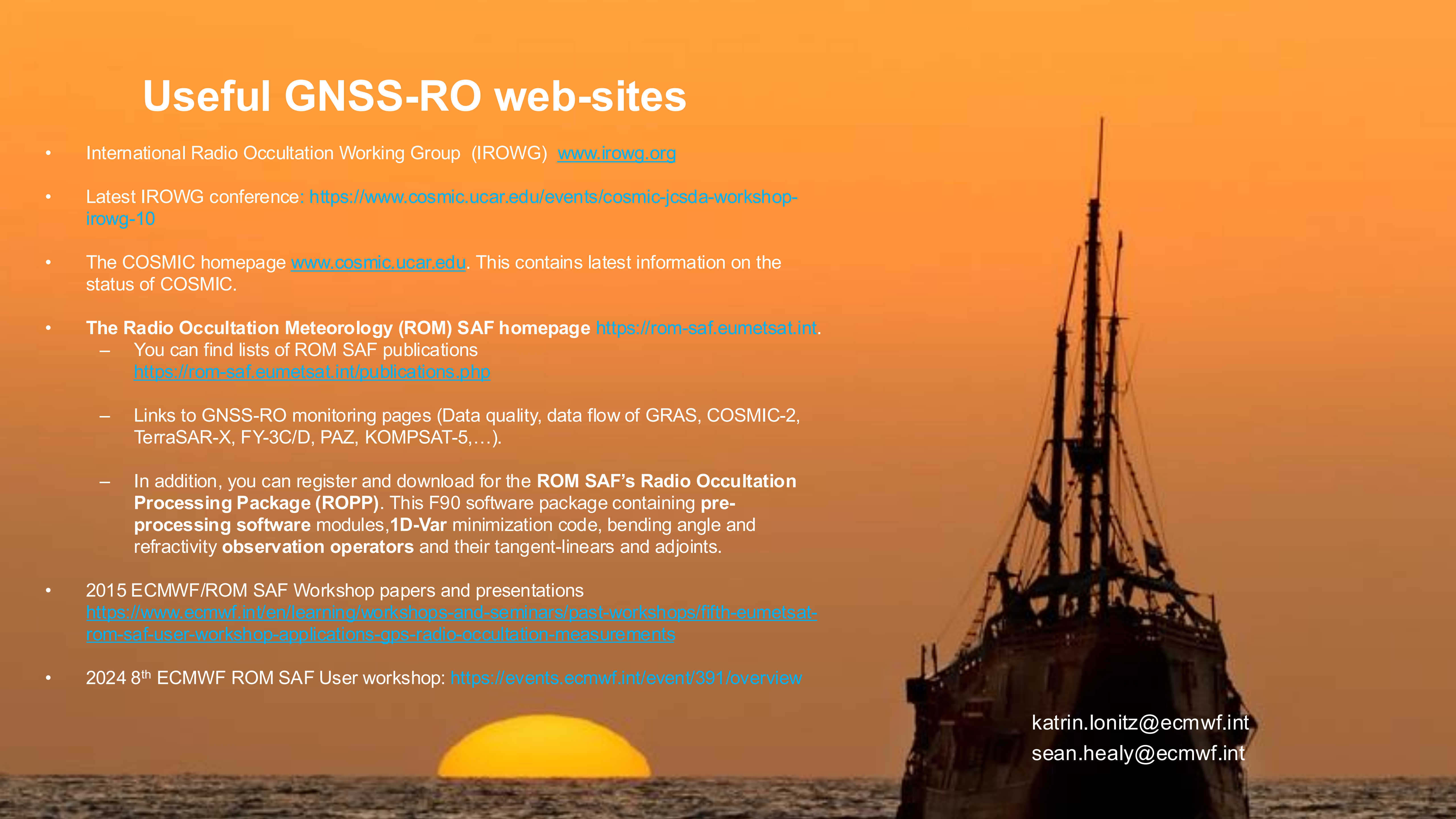
The 2D operator requires NWP information interpolated to a plane in the vertical, i.e. **interpolated from a number of model columns.**

Improvement in GNSS-RO (o-b) departure statistics with 2D approach



Summary

- GNSS-RO is a satellite-to-satellite active limb measurement.
- We outlined the basic physics of the GNSS-RO technique and the “classical” temperature retrieval. Be wary of classical temperature retrievals above 35-40 km. They mainly contain a-priori information.
- GNSS-RO Measurements **do not require bias correction and are insensitive to clouds**. GNSS-RO has **very good vertical resolution**, but poor horizontal resolution (~450 km average).
- Information content studies suggest GNSS-RO should provide good temperature information in the upper troposphere and lower/mid stratosphere. Operational assimilation and recent OSEs supports this.
- The 1D operator is quite simple. A 2D operator has been implemented at ECMWF. This improves the modelling of observations.
- More in the next lecture!



Useful GNSS-RO web-sites

- International Radio Occultation Working Group (IROWG) www.irowg.org
- Latest IROWG conference: https://www.cosmic.ucar.edu/events/cosmic-jcsda-workshop-irowg-10
- The COSMIC homepage www.cosmic.ucar.edu. This contains latest information on the status of COSMIC.
- **The Radio Occultation Meteorology (ROM) SAF homepage** https://rom-saf.eumetsat.int.
  - You can find lists of ROM SAF publications https://rom-saf.eumetsat.int/publications.php
  - Links to GNSS-RO monitoring pages (Data quality, data flow of GRAS, COSMIC-2, TerraSAR-X, FY-3C/D, PAZ, KOMPSAT-5,…).
  - In addition, you can register and download for the **ROM SAF's Radio Occultation Processing Package (ROPP)**. This F90 software package containing **pre-processing software** modules,**1D-Var** minimization code, bending angle and refractivity **observation operators** and their tangent-linears and adjoints.
- 2015 ECMWF/ROM SAF Workshop papers and presentations https://www.ecmwf.int/en/learning/workshops-and-seminars/past-workshops/fifth-eumetsat-rom-saf-user-workshop-applications-gps-radio-occultation-measurements
- 2024 8th ECMWF ROM SAF User workshop: https://events.ecmwf.int/event/391/overview

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