Improvement of Current Refraction Modeling in Satellite Laser Ranging (SLR) by Ray Tracing through Meteorological Data

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Outline

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Introduction

- Atmospheric refraction introduces significant errors in Satellite Laser Ranging (SLR) at present
- Current zenith delay model (M-P) has sub-millimeter accuracy
- Mapping function has sub-centimeter accuracy down to 10º elevation
- All models assume spherically symmetric atmosphere
- Need to account for horizontal gradients in refractivity to improve models

Motivation

- Horizontal gradients - largest source of error in SLR
- Need to be accounted for to improve accuracy of refraction corrections
- Introduce centimeter-level errors at low elevation angles
- Predominantly a function of temperature gradients
- Vary by season, latitude dependence, topography and proximity to large bodies of water
- We look at AIRS and NCEP results during 2004 for a set of core SLR stations

AIRS ray tracing

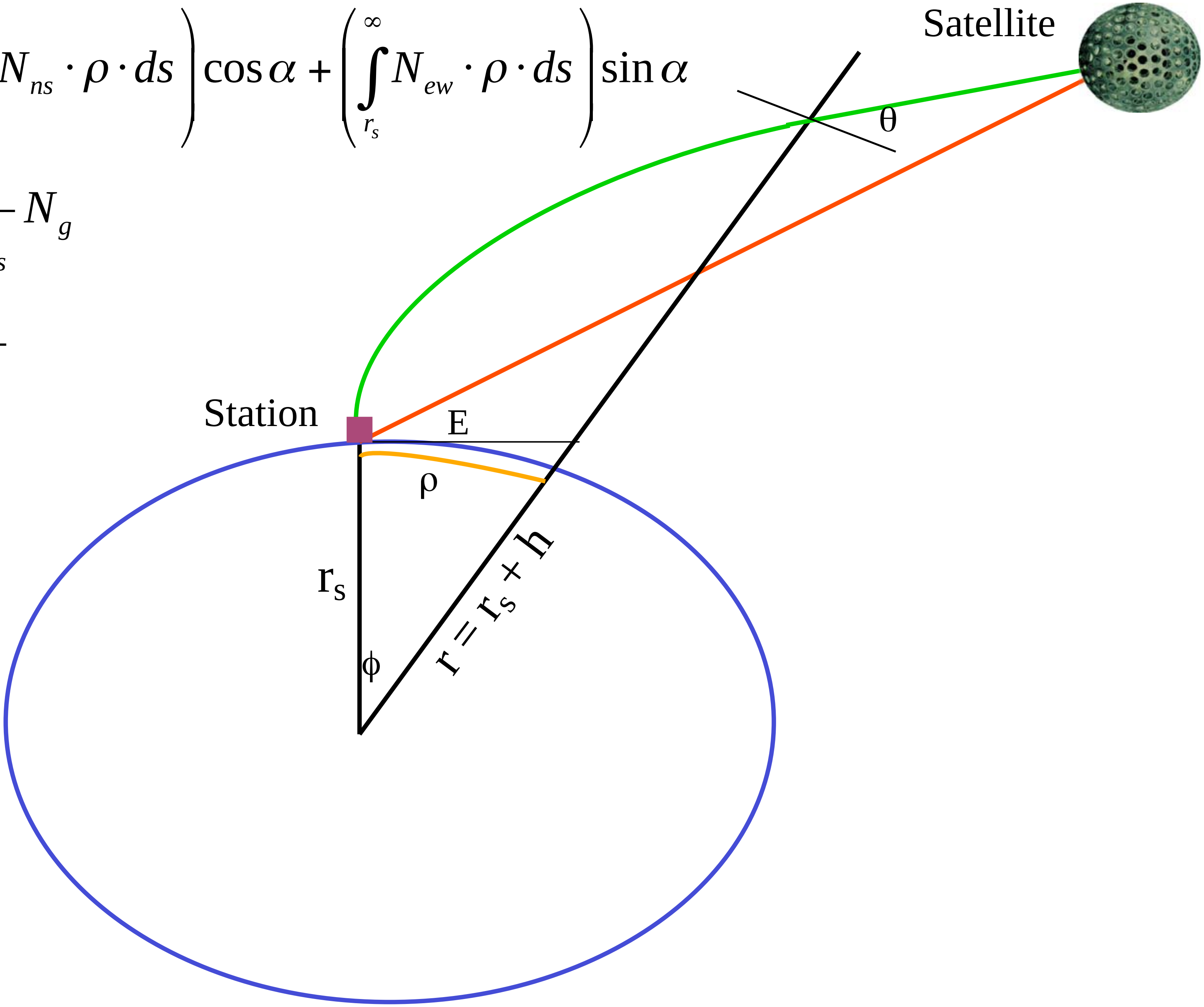
- Atmospheric Infrared Sounder (AIRS)
  - 100 levels from surface to 0.1 mb
  - Granules are 1600 (EW) x 2300 (NS) km
  - 50 km resolution
  - Temperature, water vapor other geophysical parameters
- Accuracy: 1.5 K/km RMS near surface, 1 K/km in troposphere, ~2 K in stratosphere
- Provides rapid and temporal global coverage
- 3d Refractivity profiles around SLR tracking stations
- ECMWF and NCEP profiles used as ‘validation’

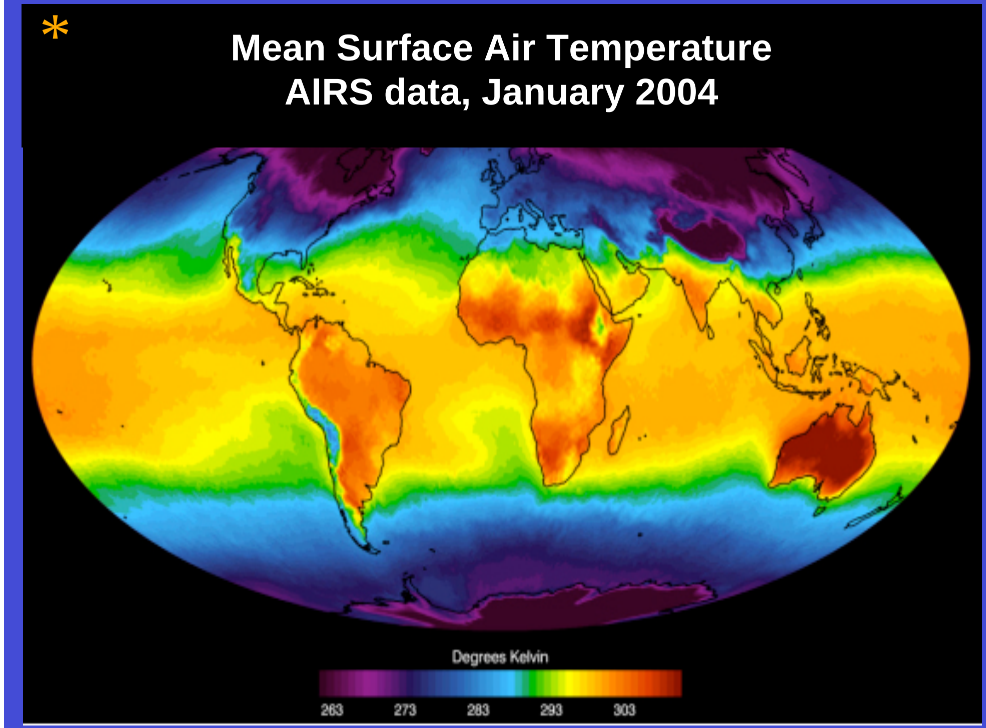
$$d_{grad} = \left(\int_{r_s}^{\infty} N_{ns}\cdot\rho\cdot ds\right)\cos\alpha + \left(\int_{r_s}^{\infty} N_{ew}\cdot\rho\cdot ds\right)\sin\alpha$$

$$N_{ns} = \frac{\partial}{\partial\rho_{ns}} N_g$$

$$ds = \frac{dr}{\sin\theta}$$

$$\rho = r\phi$$





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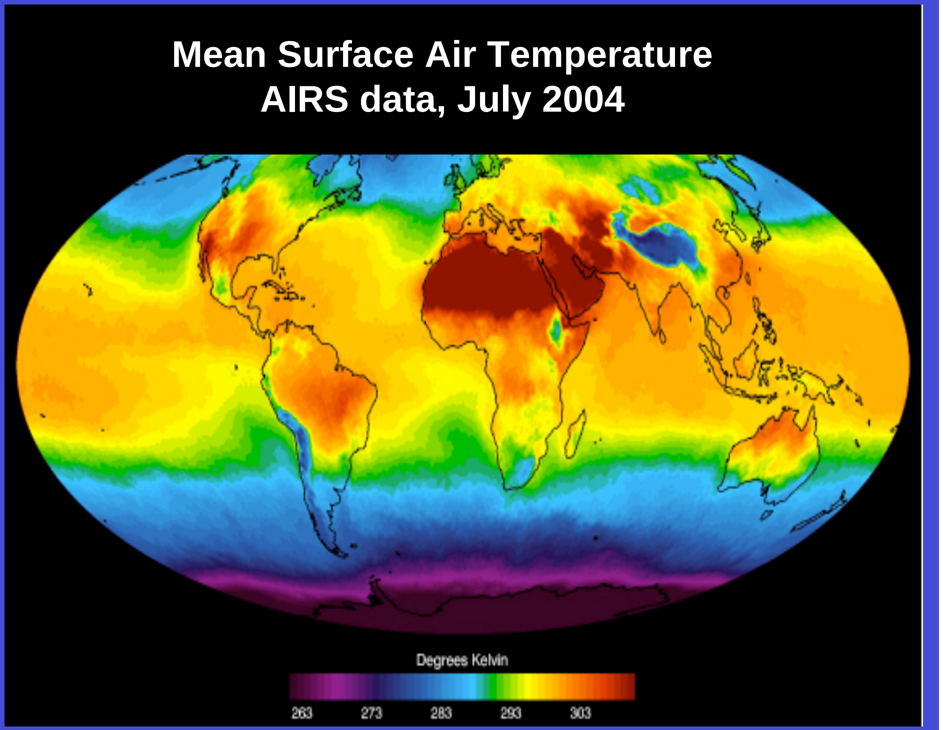
Mean Surface Air Temperature
AIRS data, January 2004



Mean Surface Air Temperature
AIRS data, July 2004

Horizontal refractivity gradients are predominantly a function of temperature gradients

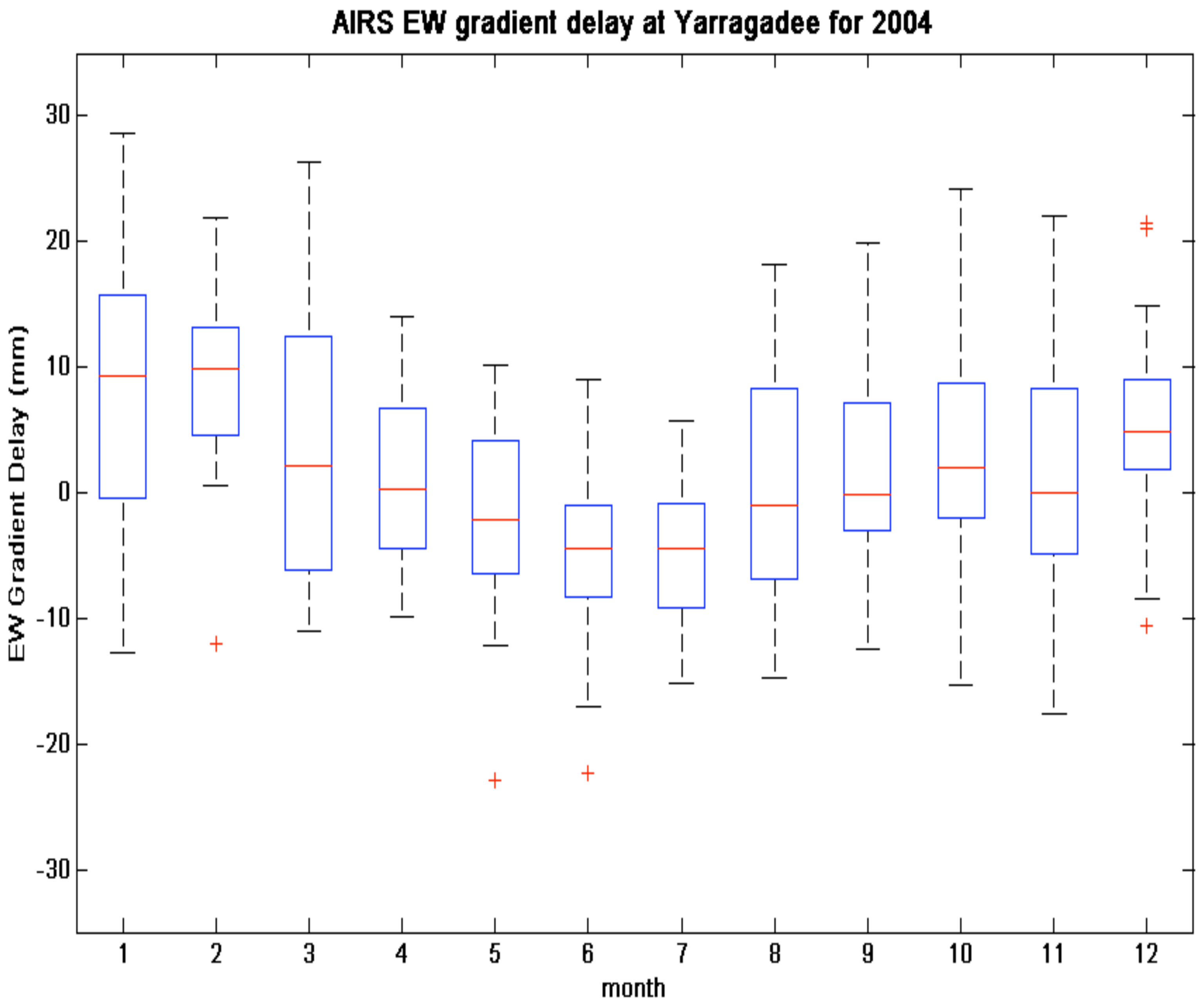
* www.airs.jpl.nasa.gov

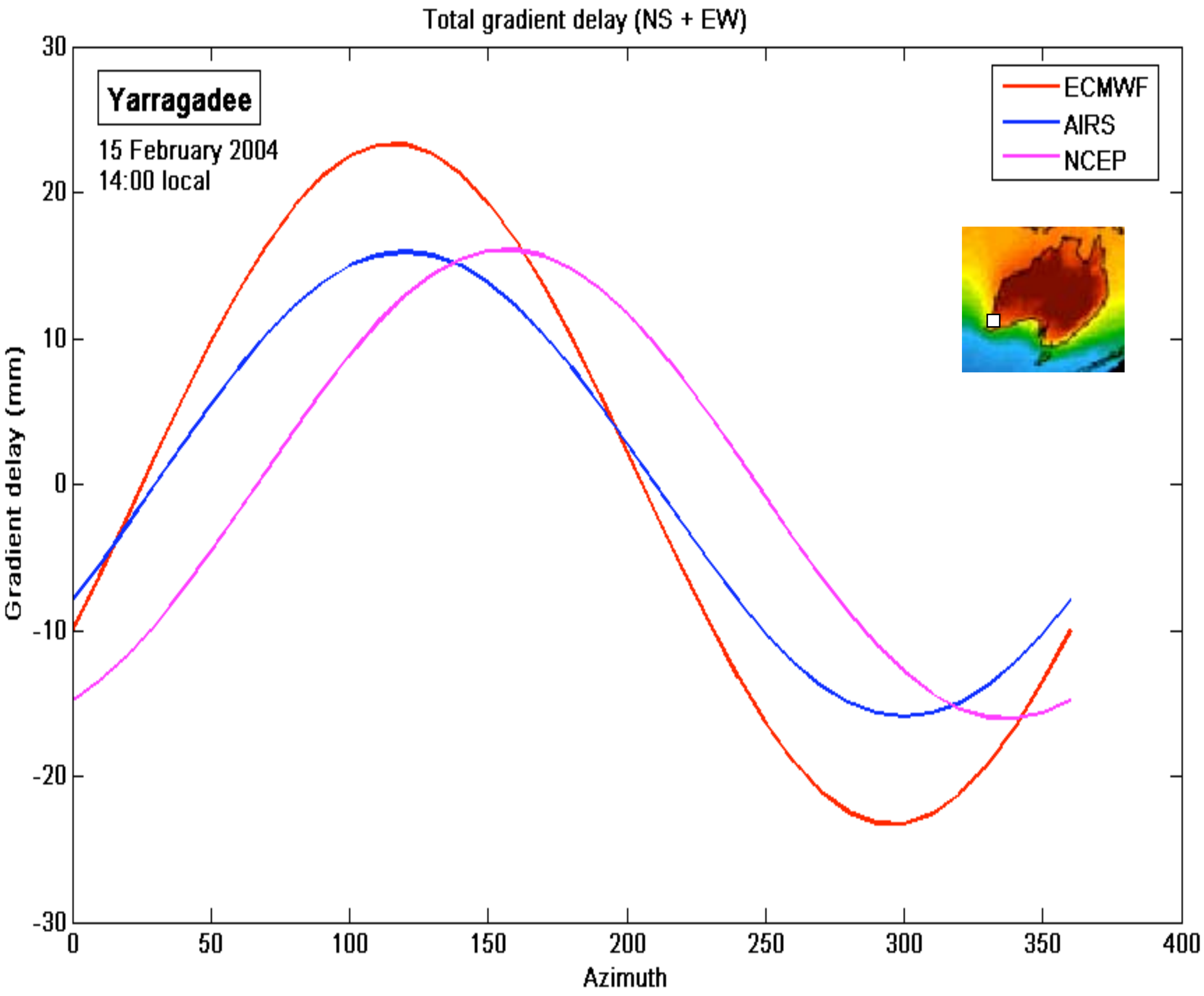
AIRS Gradient delays at 10 degrees elevation for Jan. 1 to Dec. 31 2004

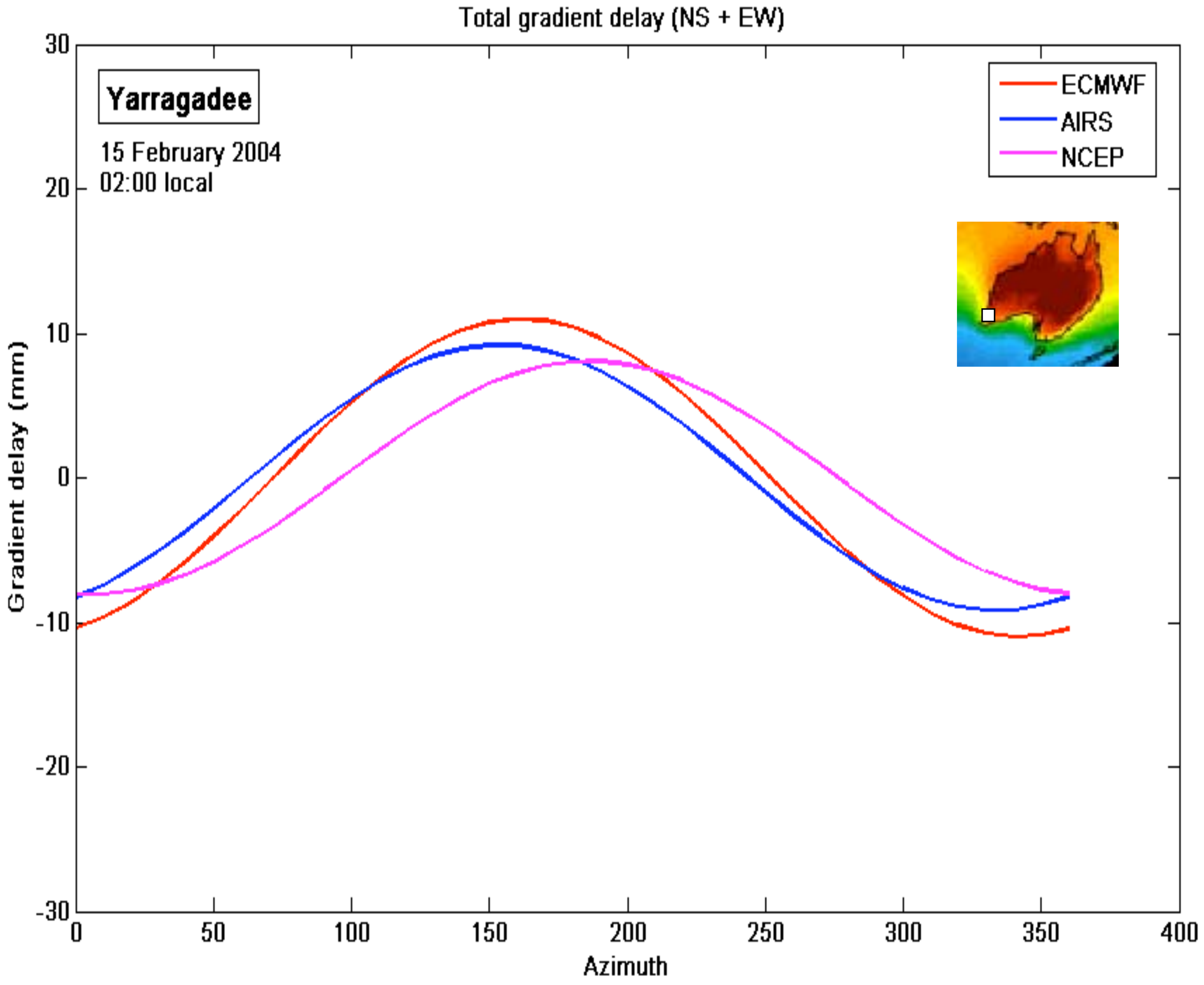
Station	NS Gradient		EW Gradient	
	Mean (mm)	Std	Mean (mm)	Std
Greenbelt, MD	-2.5	11.9	-1.5	9.8
Monument Peak, CA	-1.5	11.0	1.8	12.3
McDonald, TX	-1.4	11.7	-2.9	9.8
Herstmonceux, England	-3.5	12.3	0.1	9.5
Zimmerwald, Switzerland	-2.2	10.8	6.9	10.3
Graz, Austria	-3.3	10.9	-0.4	8.7
Matera, Italy	-2.5	11.5	1.1	10.0
Hartebeesthoek, South Africa	1.0	8.1	1.8	8.3
Mt Stromlo, Australia	2.0	11.0	4.5	10.3
Yarragadee, Australia	1.3	9.5	1.7	9.7

NCEP Gradient delays at 10 degrees elevation for Jan. 1 to Dec. 31 2004

Station	NS Gradient		EW Gradient	
	Mean (mm)	Std	Mean (mm)	Std
Greenbelt, MD	-0.9	14.8	-4.6	10.7
Monument Peak, CA	-1.5	14.7	-1.7	12.7
McDonald, TX	-1.7	15.2	-2.1	12.4
Herstmonceux, England	-2.7	14.6	2.0	14.0
Zimmerwald, Switzerland	-5.0	14.9	1.8	13.7
Graz, Austria	-7.3	14.6	0.1	13.6
Matera, Italy	-3.6	14.9	0.9	12.0
Hartebeesthoek, South Africa	3.6	11.7	1.9	7.3
Mt Stromlo, Australia	2.7	13.3	-2.9	9.5
Yarragadee, Australia	4.5	10.5	-1.8	5.9

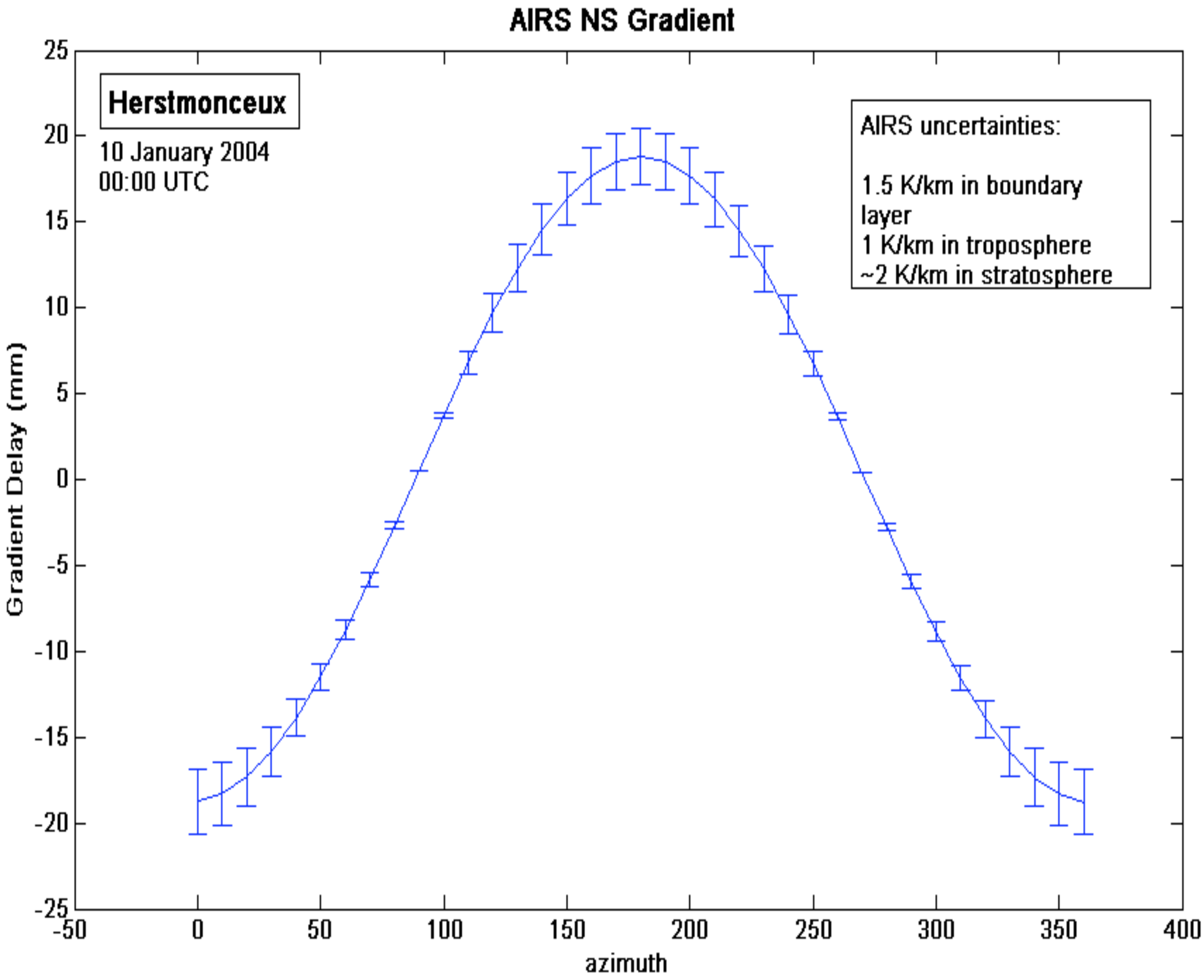

AIRS EW gradient delay at Yarragadee for 2004
EW Gradient Delay (mm)
30
20
10
0
-10
-20
-30
1
2
3
4
5
6
7
8
9
10
11
12
month


Total gradient delay (NS + EW)
Yarragadee
15 February 2004
14:00 local
ECMWF
AIRS
NCEP
Gradient delay (mm)
Azimuth
30
20
10
0
-10
-20
-30
0
50
100
150
200
250
300
350
400


Total gradient delay (NS + EW)
Yarragadee
15 February 2004
02:00 local
ECMWF
AIRS
NCEP
Gradient delay (mm)
30
20
10
0
-10
-20
-30
0
50
100
150
200
250
300
350
400
Azimuth

AIRS Gradient delays at 10 degrees elevation for Jan. 1-Dec. 31 2004

Station	Season	Time of day	NS Gradient RMS (mm)	EW Gradient RMS (mm)
Yarragadee	Summer	day	10.5	15.6
		night	6.5	9.9
	Winter	day	11.6	10.3
		night	9.1	8.4
Herstmonceux	Summer	day	14.1	10.1
		night	12.8	9.4
	Winter	day	13.8	9.7
		night	11.1	9.1



AIRS uncertainties:

1.5 K/km in boundary layer
1 K/km in troposphere
~2 K/km in stratosphere

Effects of ray tracing on real SLR data

- AIRS/ECMWF/NCEP data temporally interpolated to coincide with station observation times.
- Surface temperature and pressures measured at station used in profiles.
- Residuals = obs – calcs (M-P model)
- Total delay = delay (2D) + gradient correction
- Full 3D ray tracing includes gradient effects
- Unification of data sources, using global set of AIRS/ECMWF/NCEP atmospheric grids

Station	Month	Method	Obs	$R - R_g$ ΔRMS mm	$R - R_g$ Δvar %	$R - R_{2d}$ ΔRMS mm	$R - R_{2d}$ Δvar %	$R - R_{tot}$ ΔRMS mm	$R - R_{tot}$ Δvar %
Yarragadee	Feb '04	**AIRS**	621	0.6	13.7	0.9	27.8	0.6	25.4
		ECMWF	621	0.8	13.9	1.5	30.0	1.1	23.9
		NCEP	621	0.8	17.7	1.0	38.0	0.8	36.6
	Aug'04	**AIRS**	568	0.2	6.5	0.4	15.0	0.3	10.0
		ECMWF	568	0.5	14.9	0.8	26.8	0.6	21.9
		NCEP	568	0.8	23.6	0.7	21.0	0.6	17.8

$R = O - C$

$R_g = O - (C + \Delta\, trop_g)$

$R_{2d} = O - (C - \Delta\, trop_{mp} + \Delta\, trop_{2d})$

$R_{tot} = O - (C - \Delta\, trop_{mp} + \Delta\, trop_{2d} + \Delta\, trop_g)$

Δvar = variance percent difference (%)

R – Residuals

O – Observed ranges

C – Calculated ranges

$\Delta\, trop_{mp}$ – model correction

$\Delta\, trop_{2d}$ – ray tracing correction

$\Delta\, trop_g$ – gradient correction

Station	Month	Method	Obs	$R - R_g$		$R - R_{2d}$		$R - R_{tot}$	
				ΔRMS mm	Δvar %	ΔRMS mm	Δvar %	ΔRMS mm	Δvar %
Zimmerwald	Feb ‘04	**AIRS**	484	0.6	12.0	1.7	16.6	1.5	12.4
		ECMWF	484	0.9	4.3	2.2	24.0	1.9	20.5
		NCEP	484	0.9	-2.7	0.7	27.6	1.1	8.5
	Aug’04	**AIRS**	769	0.6	20.8	1.0	20.1	1.1	23.4
		ECMWF	769	1.0	18.9	2.5	30.0	2.0	30.1
		NCEP	769	0.4	-9.0	0.4	3.6	0.3	-7.8

$R = O - C$

$R_g = O - (C + \Delta\ trop_g)$

$R_{2d} = O - (C - \Delta\ trop_{mp} + \Delta\ trop_{2d})$

$R_{tot} = O - (C - \Delta\ trop_{mp} + \Delta\ trop_{2d} + \Delta\ trop_g)$

Δvar = variance percent difference (%)

R – Residuals

O – Observed ranges

C – Calculated ranges

$\Delta\ trop_{mp}$ – model correction

$\Delta\ trop_{2d}$ – ray tracing correction

$\Delta\ trop_g$ – gradient correction

Conclusions

- Horizontal gradients need to be accounted for to improve SLR measurements for mm-geodesy
- Only significant at low elevation angles and are strongly correlated to temperature gradients
- Ray tracing (2D + gradients) reduce residual statistics by up to 2 mm RMS and 30% in variance
- Unification of data sources will help, using AIRS/ECMWF/NCEP atmospheric grids

- Atmospheric Infrared Sounder (AIRS)
  - 100 levels from surface to 0.1 mb
  - Granules are 1600 (EW) x 2300 (NS) km
  - 40.5 km resolution within grid
  - Data is obtained twice-daily
- ECMWF
  - 60 levels from surface to 0.1 mb
  - 0.5° resolution
  - Analysis files at 00, 06, 12 and 18 hrs UTC
- NCEP
  - 17 levels from surface to 10 mb
  - 2.5° resolution
  - Analysis files at 00, 06, 12 and 18 hrs UTC

$$d_{atm} = 10^{-6} \int_{atm} N \cdot ds + \left[\int_{ray} ds - \int_{vac} ds \right]$$

$$N_h = 0.82\, f_h(\lambda) Z_d R_d \frac{M_d}{ZR} \left[\frac{P}{T} - (1 - \varepsilon) \frac{e}{T} \right]$$

$$N_{nh} = -0.82\varepsilon\, f_h(\lambda) \left(\frac{Z_d}{Z} \right) \left(\frac{e}{T} \right) + 0.72\, f_{nh}(\lambda) \left(\frac{Z_w}{Z} \right) \left(\frac{e}{T} \right)$$

$$P = P_o \left(\frac{T}{T_o} \right)^{\frac{g}{R_d \alpha}}$$

$$\rho = \frac{h}{\tan E} \left(1 - \frac{1}{2} \frac{\cos^2 E}{\tan^2 E} \frac{h}{r_s} \right)$$