Atmosphere and Climate Explorer

Based on GPS, GALILEO, and LEO-LEO Radio Occultation

ACE+ Objectives, Mission Concept, and Science Team Building

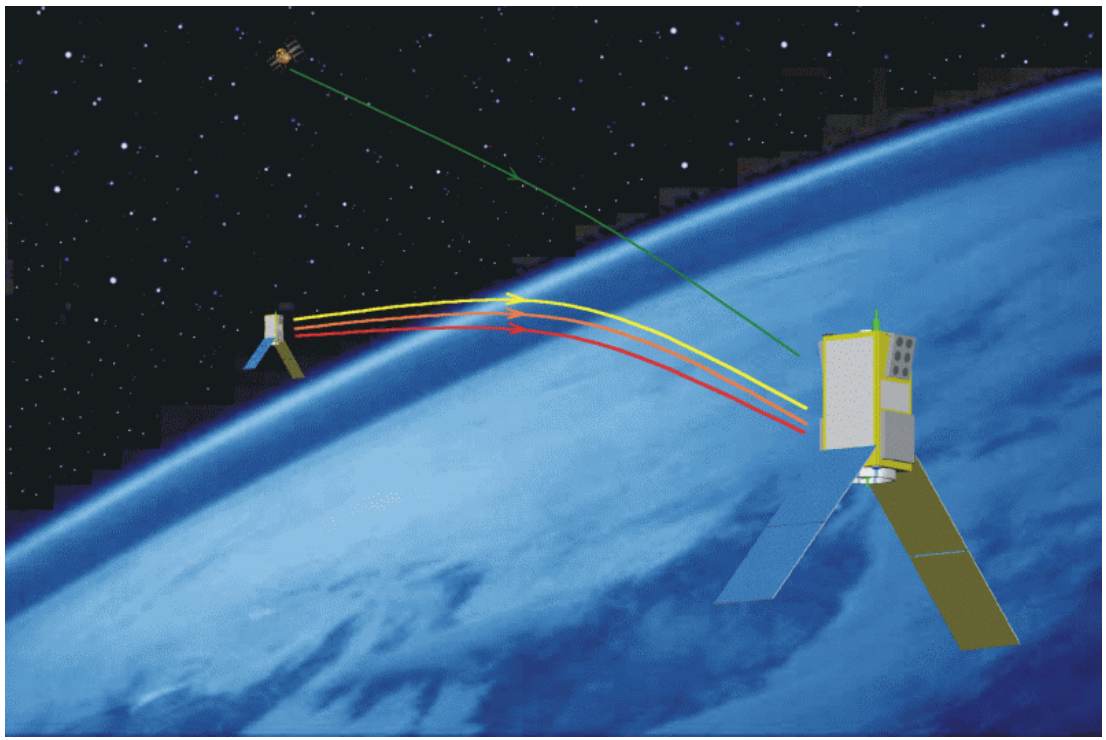
Gottfried Kirchengast

Institute for Geophysics, Astrophysics, and Meteorology (IGAM),
University of Graz, Austria
(*www.uni-graz.at/igam-arsclisys*)

The ACE+ Case
One Page Preview

ACE+ – Atmosphere and Climate Explorer based on GPS, GALILEO, and LEO-LEO radio occultation

ESA Mission; Science: Lead Investigators P. Hoeg (DMI) and G. Kirchengast, Mission Advisory Group (appointed by ESA), International Science Team (partners worldwide); Industry: European Consortium (decided on by end 2003 after competitive phase A)



Basic Facts:

- selected by ESA in May 2002 as top priority future Earth Explorer Opportunity Mission
- 4 LEO satellites exploiting GPS, GALILEO, and LEO-crosslink signals
- primary science objectives on climate plus a series of others (NWP, atmos. physics, etc.)
- phase A 2003, after confirmation end 2003 phases B-D until 2007, operations 2007/08-2012

The ACE+ Case
Outline

1. Setting the Scene

- Primary Issue of Concern

2. The ACE+ Mission

- Goals and Objectives
- Observation Requirements
- Limitations of other Data
- Measurement Methodology
- Observation Performance
- Draft System Concept

3. The Essence

- Unique Contributions of ACE+

4. ACE+ Evaluation and Next Steps

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- **Primary Issue of Concern**

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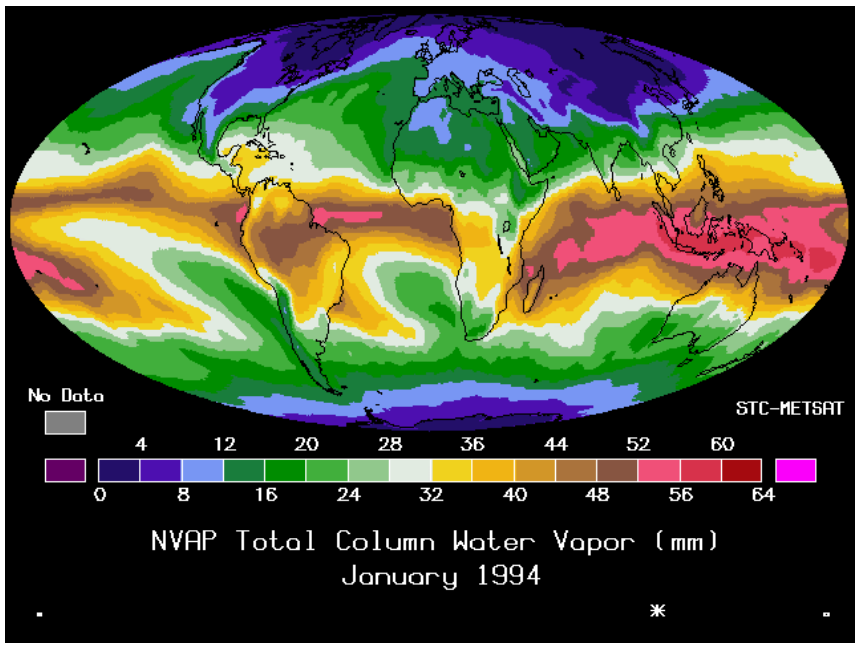
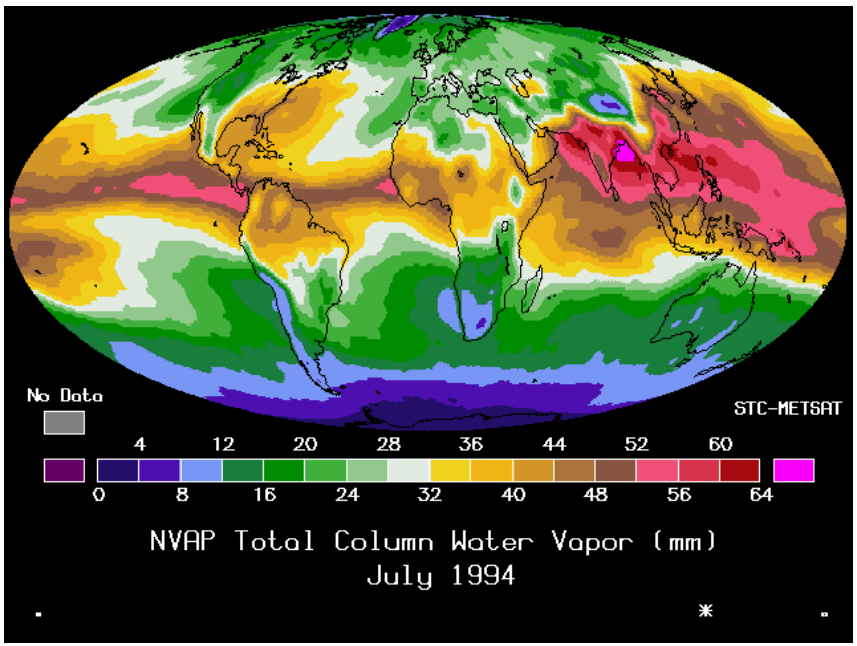
Primary Issue of Concern: Climate Change

- Increasing evidence exists that the Earth's climate is currently changing (e.g., IPCC 2001 Report). The changes are most pronounced in the most variable component of the Earth system, the atmosphere.

Variability of Atmospheric Humidity (1)



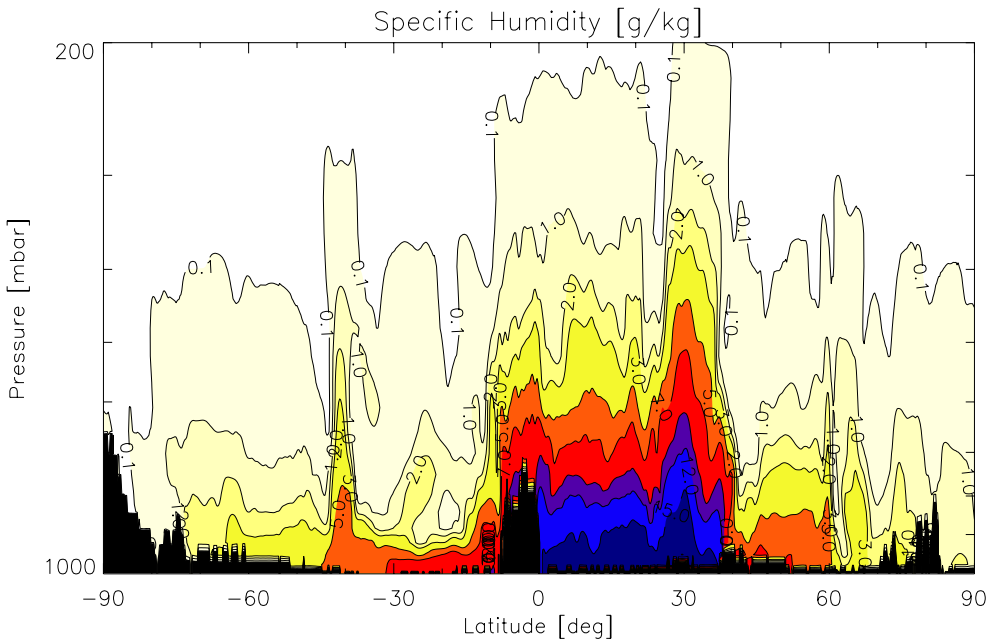
[Source: NASA Water Vapor Project CD-Rom; Sci&Tech Corp., 1997]



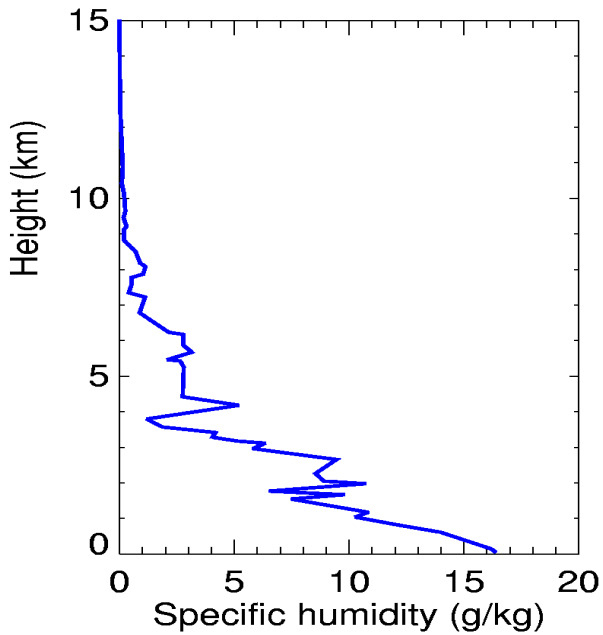
Column Water Vapour Monthly Map January 1994 (NVAP Project)

Column Water Vapour Monthly Map July 1994 (NVAP Project)

Variability of Atmospheric Humidity (2)



Latitude-Height Slice of Humidity (ECMWF analysis, 15 Sep 1999, 12UTC, 79°W)

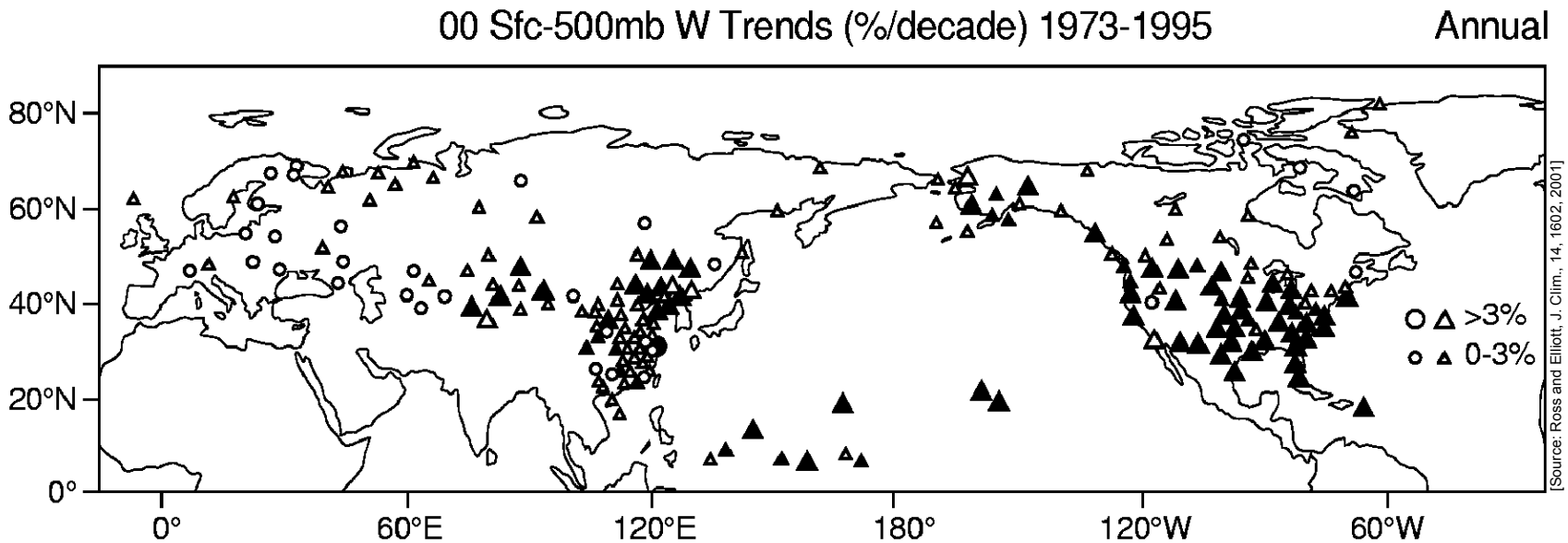


Humidity Profile (RAOB, Kauai, Hawaii, 1 Oct 2000, 12UTC)

Primary Issue of Concern: Climate Change

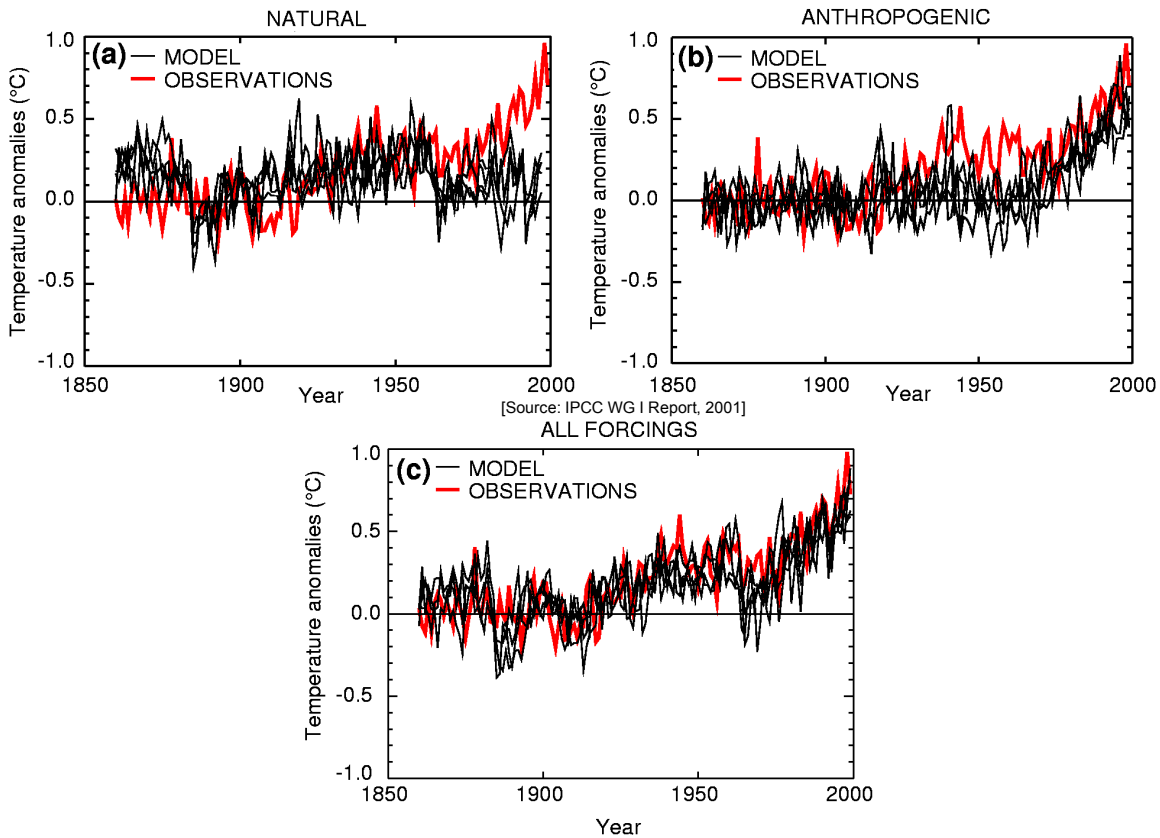
- Increasing evidence exists that the Earth's climate is currently changing (e.g., IPCC 2001 Report). The changes are most pronounced in the most variable component of the Earth system, the atmosphere.
- Key indicators include:
  - Humidity and temperature in the troposphere tend to increase

Recent Climatic Change in Humidity



Annually-averaged trends in Surface–500hPa column water vapour (RAOB data, 00UTC, period 1973–1995; *triangles:* positive trends, *circles:* negative trends, *filled triangles:* trends significant at 95%)

Recent Climatic Change in Temperature



Global-mean near surface temperature change relative to 1880–1920 mean
(*red/heavy:* observations, *light:* model simulations with different forcings)

Primary Issue of Concern: Climate Change

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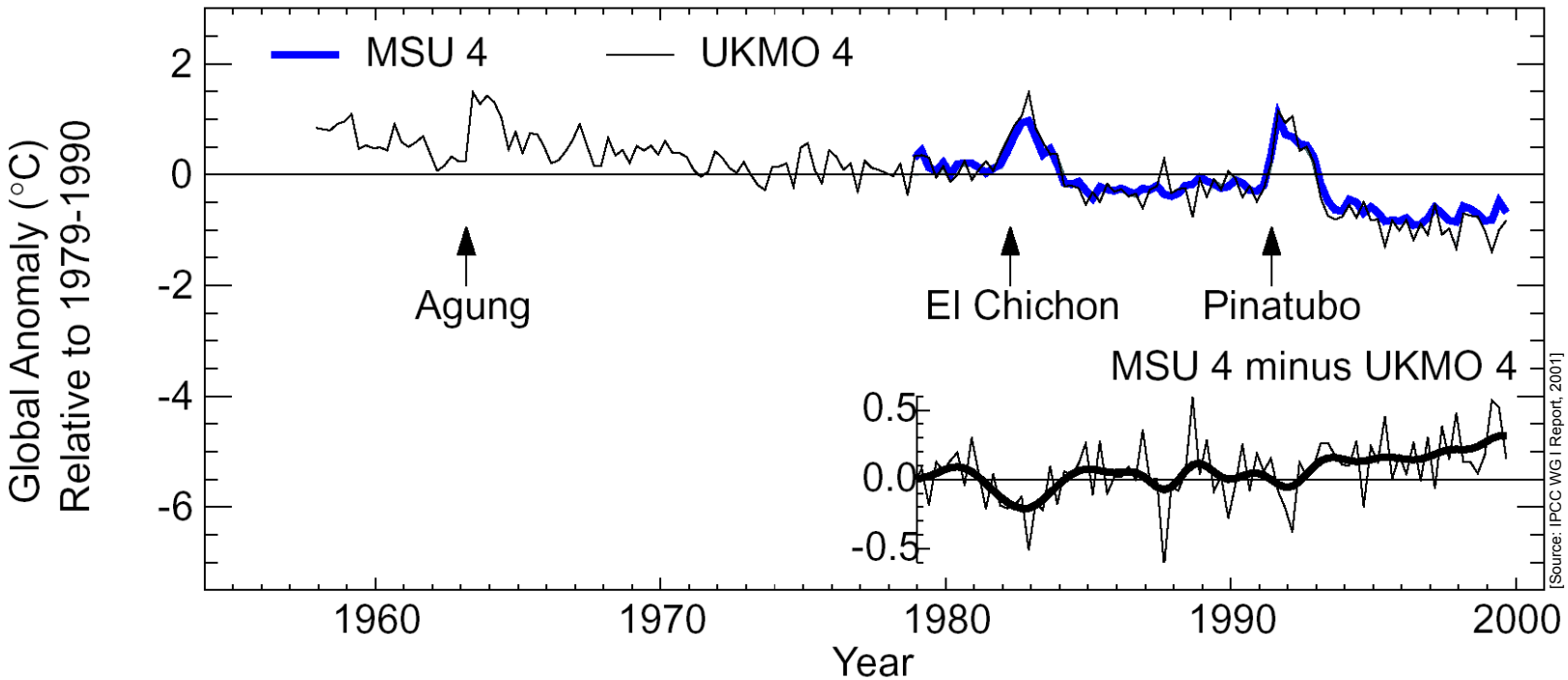
  - Humidity and temperature in the troposphere tend to increase
  - Stratospheric temperatures tend to decrease

Recent Stratospheric Temperature Change

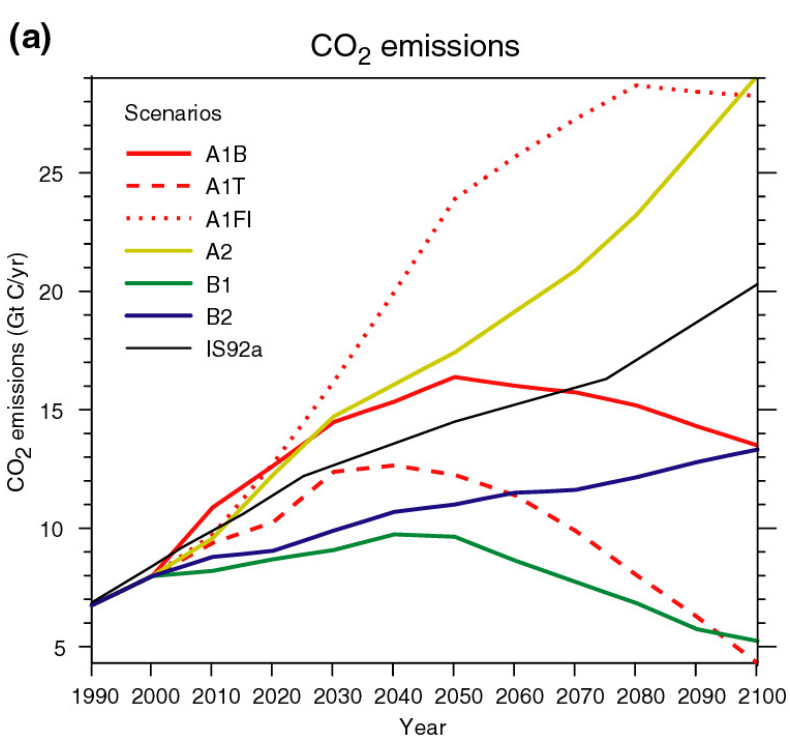


Global temperature change in the lower stratosphere during the last decades (*MSU:* MSU satellite data, *UKMO:* RAOB-based data; inset: difference)

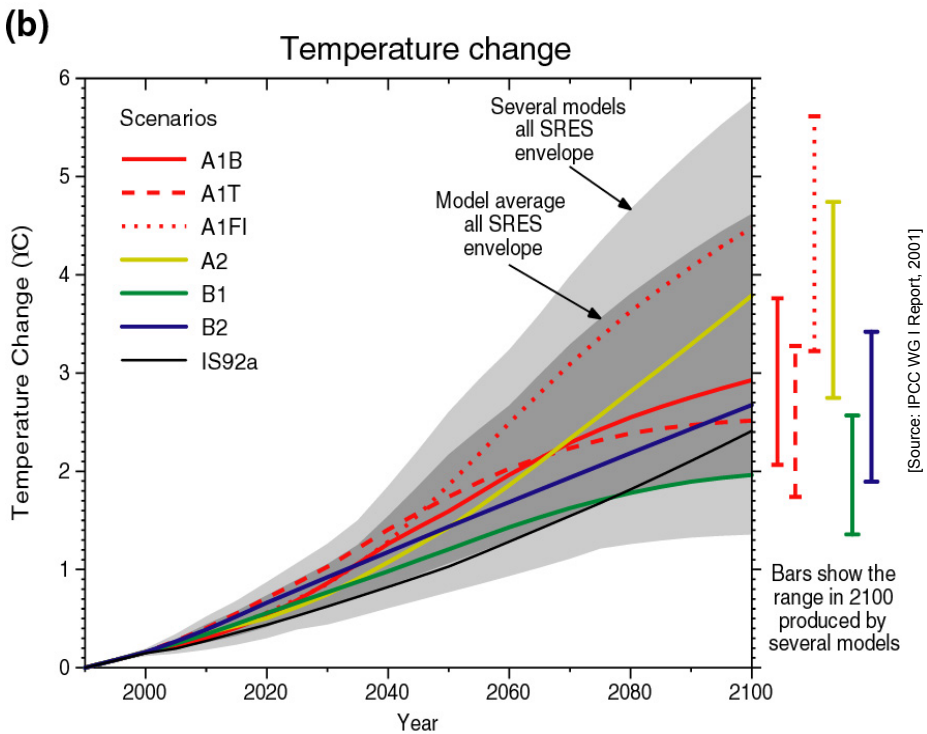
Primary Issue of Concern: Climate Change

- Increasing evidence exists that the Earth's climate is currently changing (e.g., IPCC 2001 Report). The changes are most pronounced in the most variable component of the Earth system, the atmosphere.
- Key indicators include:
  - Humidity and temperature in the troposphere tend to increase
  - Stratospheric temperatures tend to decrease
- It is likely that these changes are associated with human-induced increases of greenhouse gas concentrations in the atmosphere.

Greenhouse Gas Emission Paths and Temperature Change Projections



a) CO_2 emission paths for several representative IPCC scenarios

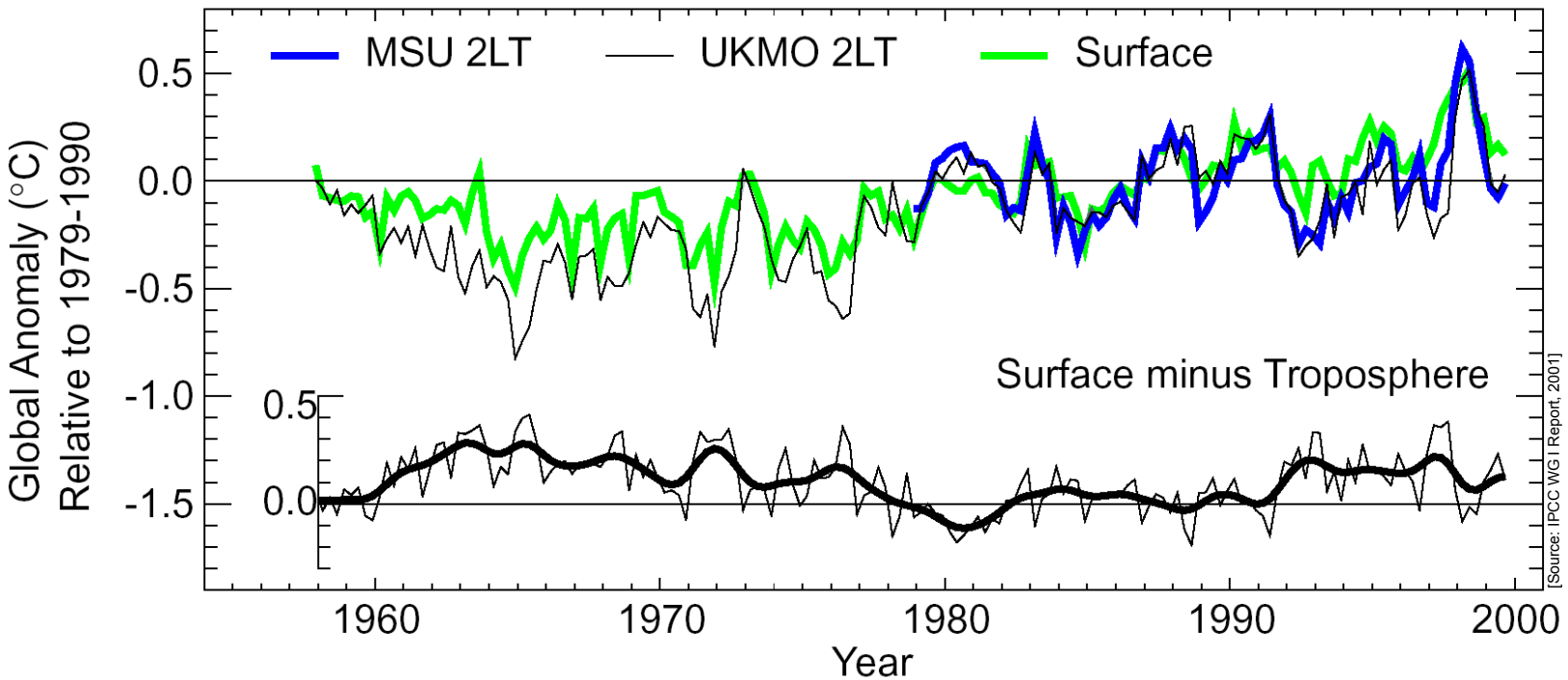


b) Corresponding near surface temperature change projections

Primary Issue of Concern: Climate Change

- Increasing evidence exists that the Earth's climate is currently changing (e.g., IPCC 2001 Report). The changes are most pronounced in the most variable component of the Earth system, the atmosphere.
- Key indicators include:
  - Humidity and temperature in the troposphere tend to increase
  - Stratospheric temperatures tend to decrease
- It is likely that these changes are associated with human-induced increases of greenhouse gas concentrations in the atmosphere.
- Natural variability of the climate system complicates the picture, rendering proper understanding of climate change very challenging.

Inadequacy of Present Observations



Global tropospheric and surface temperature data from different sources (*MSU:* MSU satellite data, *UKMO:* RAOB-based data, *Surface:* surface data; inset: difference between surface and RAOB-based data)

The Need for Climate Change Observations

...from the 9 **"high priority areas for action"** noted in the recent **IPCC 2001 report** (Summary for Policymakers, IPCC Working Group I, page 17):

*"**- sustain and expand the observational foundation for climate studies by providing accurate, long-term, consistent data** including implementation of a strategy for integrated global observations."*

- Despite an increasing body of observations, data on the fundamental atmospheric parameters humidity and temperature are still of inadequate quality and coverage.
- **Adequate humidity and temperature data are thus urgently needed** for improved monitoring, modelling, analysis, and prediction of (human-induced) climate change and understanding of its consequences.

is the Mission of Choice to provide such data!

The ACE+ Case
2. The ACE+ Mission

1. Setting the Scene
   - Primary Issue of Concern

2. The ACE+ Mission
- **Goals and Objectives**
- **Observation Requirements**
- **Limitations of other Data**
- **Measurement Methodology**
- **Observation Performance**
- **Draft System Concept**

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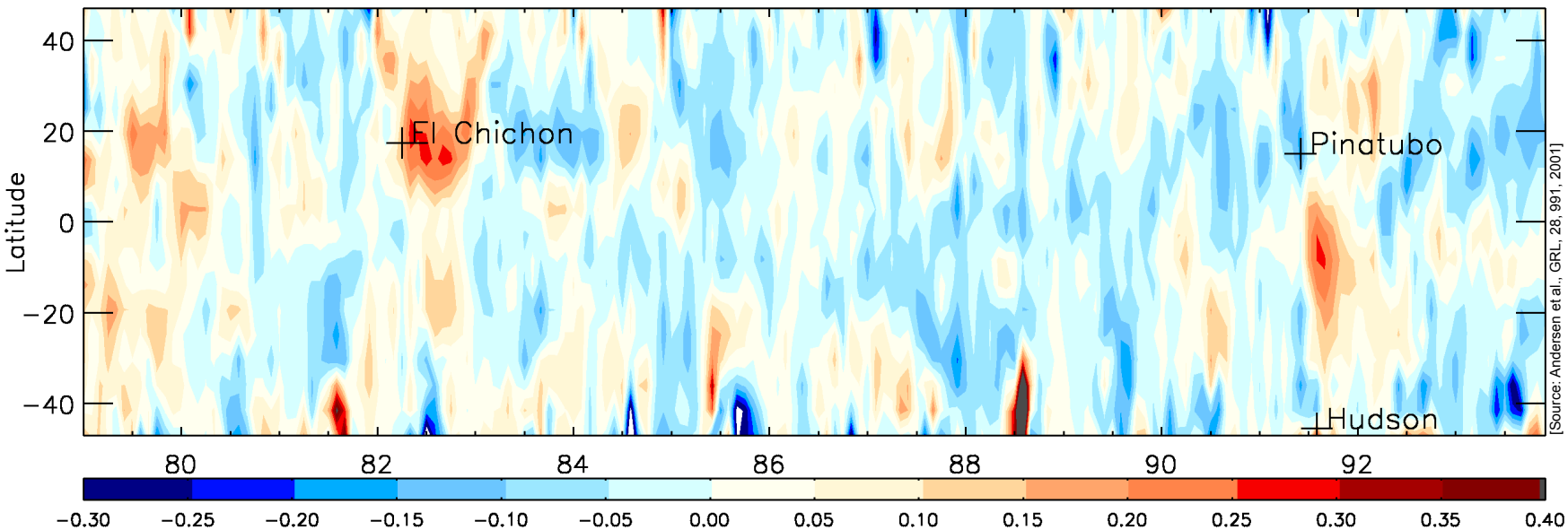
ACE+ Primary Mission Goals

Primary goals focus on climate and include:

- To monitor climatic variations and trends at different vertical levels and throughout all seasons. This to improve our understanding of the climate system as well as to detect the different fingerprints of global warming.
- To improve the understanding of climatic feedbacks defining the magnitude and characteristics of climate changes in response to given forcings.
- To validate the simulated mean climate and its variability in global climate models.
- To improve and tune – via data assimilation – the parameterization of unresolved processes in climate models and to detect variations in external forcing of climate.

Detection of External Forcing of Climate



Anomalies in the zonal mean of 24 hr temperature analysis increments (anomalies relative to average annual cycle, units K/day; 30hPa level, period 1979–1993, use of ECMWF re-analysis data set “ERA15”)

ACE+ Objectives

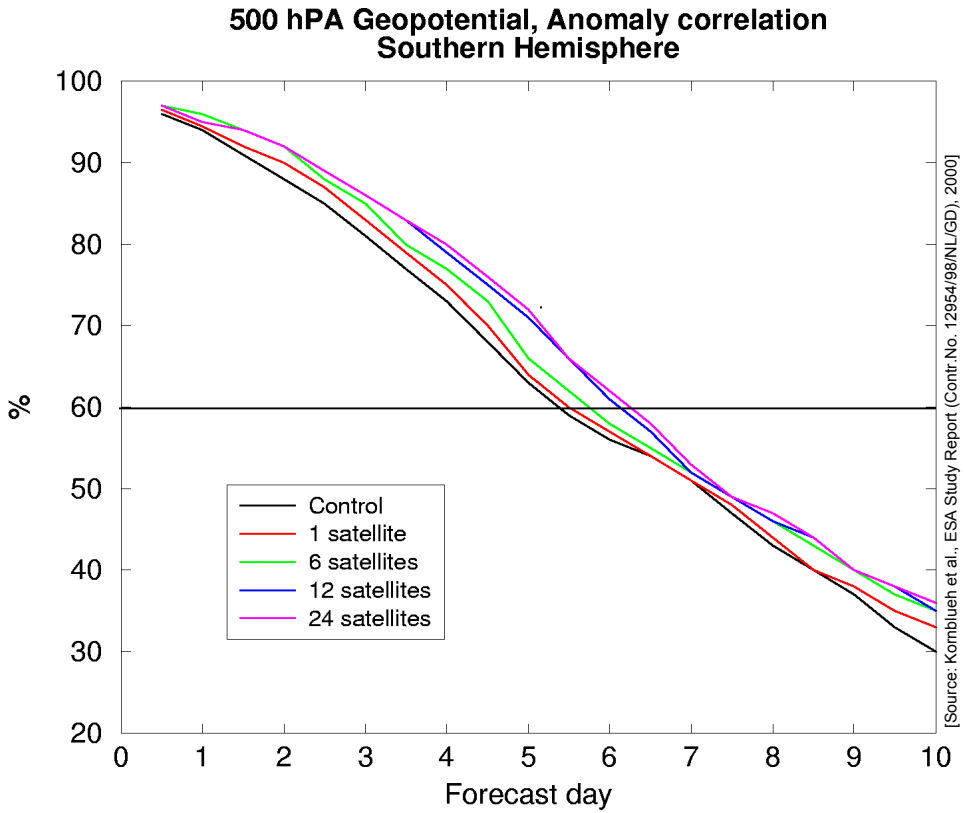
Main Objectives:

- To establish a highly accurate (< 0.003 g/kg or < 3 %, whatever is larger) and vertically resolved (0.5–1 km) climatology of humidity in the troposphere with global all-weather measurements of its concentration.
- To establish a highly accurate (< 0.2 K) and vertically resolved (0.5–1 km) climatology of temperature in the troposphere and the stratosphere with global all-weather measurements of its vertical structure.
- To support research on climate variability and climate change and on validation and improvement of atmospheric models.
- To support advancements of NWP (Numerical Weather Prediction).
- To support analysis and validation of data from other space missions.
- To demonstrate a novel active self-calibrating atmosphere sounding method.

Spin-Off Objectives:

- Ionospheric climate & weather and space weather investigations.
- Assessing and improving present water vapor attenuation models.

Indication of Impact of ACE+-like Data on NWP



Forecast skill improvement due to GNSS-LEO data from ACE+-like constellations (1, 6, 12, 24 LEO satellites; *Control:* no ingestion of GNSS-LEO data)

ACE+ LEO-LEO Observation Requirements

		Specific Humidity	Temperature
Horizontal Domain		**Global**	
Horizontal Sampling		< 1500 km	
Vertical Domain		surface–20 km	surface–50 km
Vertical Sampling	**LT/0-5 km** **HT/ 5-15** **LS/15-35** **HS/35-50**	0.2–1 km 0.5–1 km 1–2 km 1–2 km	0.2–1 km 0.5–1 km 0.5–1 km 1–2 km
Time Sampling		6–24 hrs	
RMS Accuracy	**LT/0-5 km** **HT/ 5-15** **LS/15-35** **HS/35-50**	0.2–1 g/kg 0.003–0.2 g/kg 0.003–0.01 g/kg [1)] –	0.5–2 K 0.5–1 K 0.5–1 K 1–3 K
Timeliness		< 30 days (Climate), < 3 hrs (NWP) [2)]	
Time Domain		> 5 years	
Long-term Stability		**< 2% / decade**	**< 0.1 K / decade**
No. of profiles/ grid box/month		> 30	

1) Applicable up to z = 20 km

2) On best effort basis (for a significant fraction of the data)

(takes due regard of WMO requirements)

ACE+ GNSS-LEO Observation Requirements

		Specific Humidity	Temperature
Horizontal Domain		**Global**	
Horizontal Sampling		< 500 km	
Vertical Domain		surface–10 km	surface–50 km
Vertical Sampling	**LT/0-5 km** **HT/ 5-15** **LS/15-35** **HS/35-50**	0.2–1 km 0.5–1 km – –	0.2–1 km 0.5–1 km 0.5–1 km 1–2 km
Time Sampling		6–12 hrs	
RMS Accuracy	**LT/0-5 km** **HT/ 5-15** **LS/15-35** **HS/35-50**	0.2–1 g/kg 0.1–0.2 g/kg [1)] – –	0.5–2 K 0.5–1 K 0.5–1 K 1–3 K
Timeliness		< 30 days (Climate), < 3 hrs (NWP) [2)]	
Time Domain		> 5 years	
Long-term Stability		**< 2% RH [3)] / decade**	**< 0.1 K / decade**
No. of profiles/ grid box/month		> 50	

(takes due regard of WMO requirements)

1) Applicable up to z = 10 km

2) On best effort basis (for a significant fraction of the data)

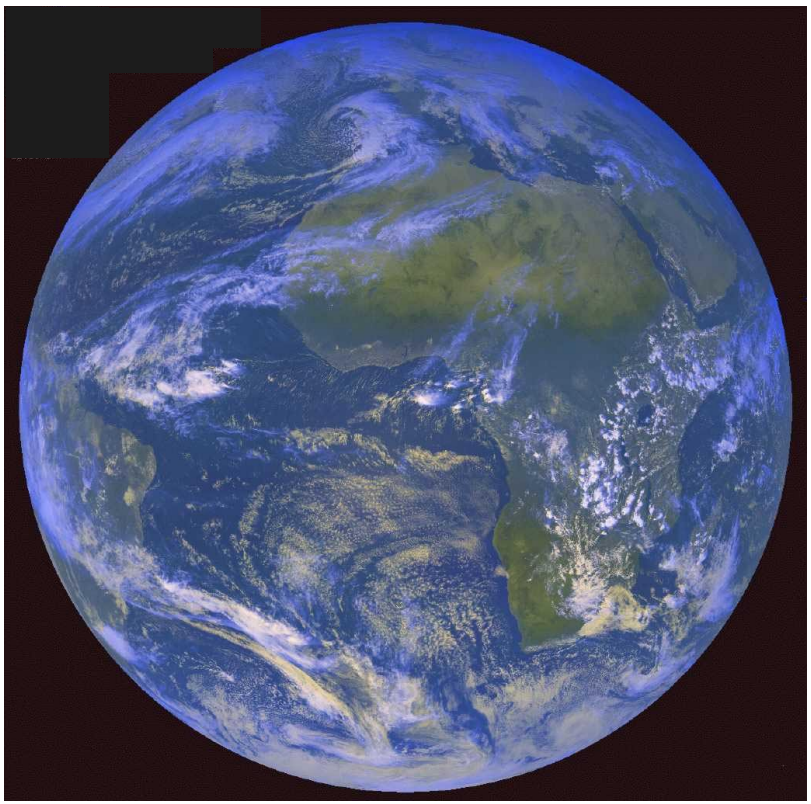
3) % RH = % relative humidity

Limitations of Data from other Sources

Other humidity and temperature data suffer from restrictions such as:

- Radiosonde data are mainly available over land masses of the northern hemisphere, commercial aircraft data along major air routes only. Thus these sources cover most areas of the world sparsely or not at all.
- Classical satellite sounding radiometers have a limited vertical resolution and measurements (i.p., optical and IR) are degraded in cloudy areas. The absolute accuracy of radiometer data depends on calibration.
- Specialised radiometric techniques such as passive MW limb sounding and solar&stellar occultation are mainly sensitive to stratospheric humidity only.
- Currently planned radio occultation missions such as GRAS on MetOp need auxiliary data to separate tropospheric humidity and temperature. Also, such single satellite missions have limited horizontal sampling.

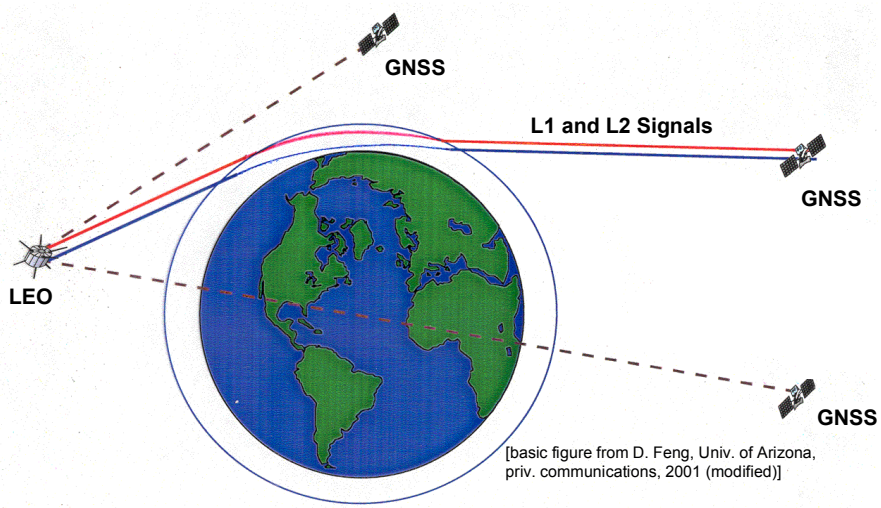
Limitation Example: Degradation Potential of Clouds

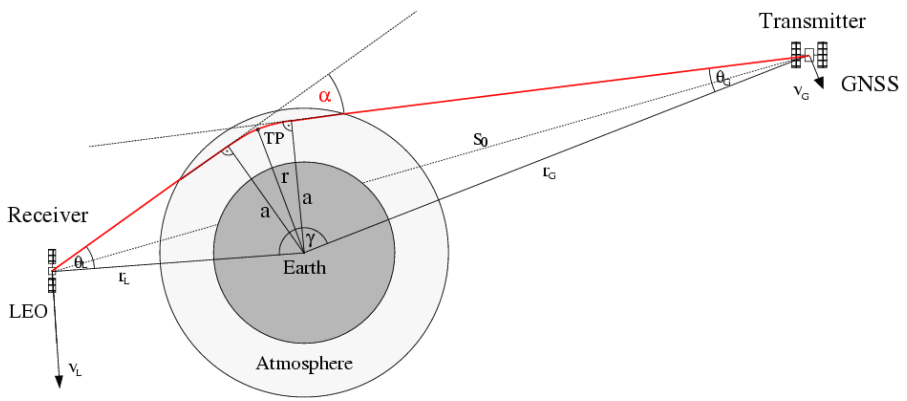


[© EUMETSAT, Meteosat Image, 1997]

Clouds cover on average ~50% of the globe (Coloured Meteosat image, vis&therm&wvap channels; 25 Nov 1997, 12:30UTC)

ACE+ Measurement Methods (1)



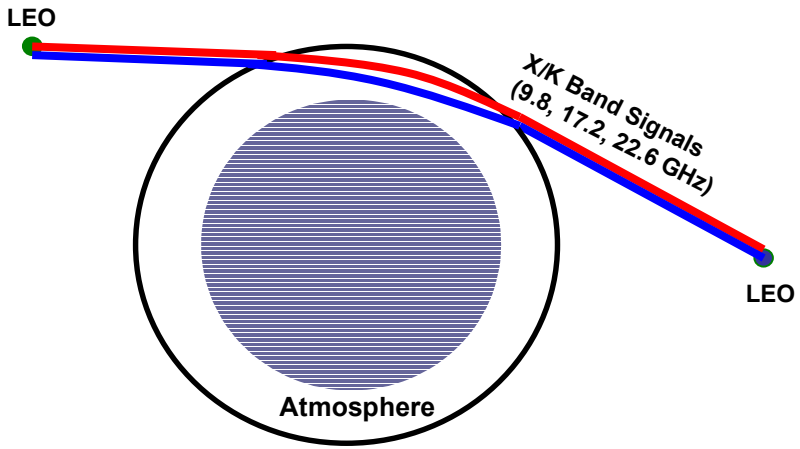


GNSS-LEO Occultation

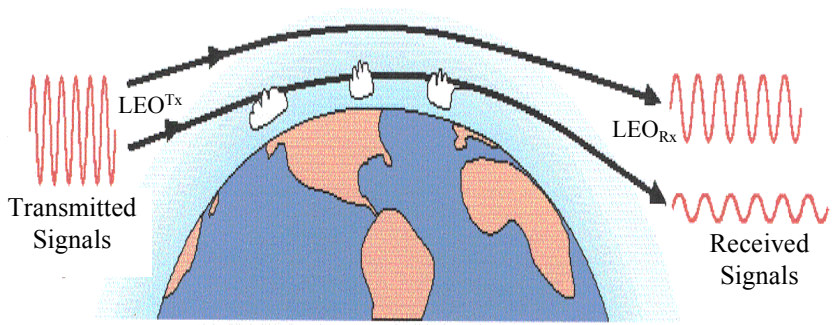
- exploits (mainly) refraction of L-band signals along limb paths
- providing measurements of phase path delay/Doppler shift
- leading via atmospheric bending angle and refractivity profiles
- to key atmosphere and climate parameters such as temperature, humidity, and geopotential height.

Inversion of the virtually well-posed and close to linear problem via
- direct inversion or
- data assimilation approach.

ACE+ Measurement Methods (2)



[basic figures from D. Feng, Univ. of Arizona, priv. communications, 2001 (modified)]



LEO-LEO Occultation

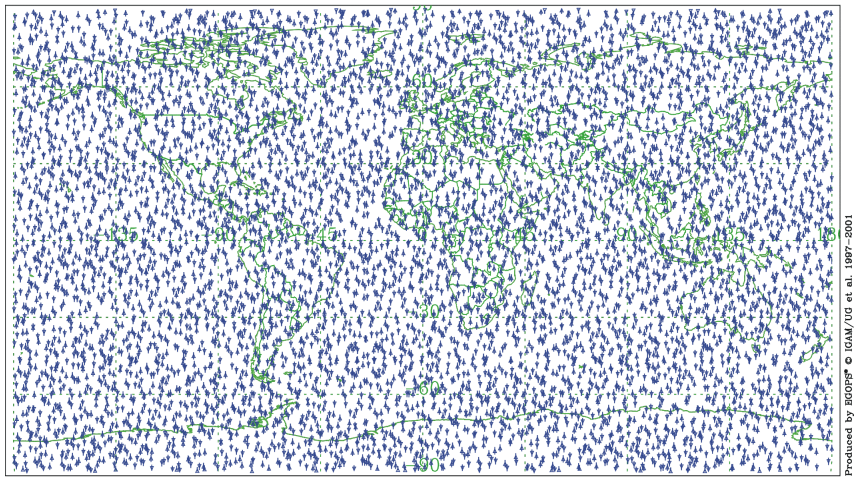
- exploits absorption & refraction of X/K-band signals along limb paths
- providing measurements of transmission and Doppler shift
- leading via absorption, bending angle, and (complex) refractivity
- to key troposphere and climate parameters such as temperature, humidity, and geopotential height.

Inversion similar to GNSS-LEO, but providing *T* and *q* independently; also solved by

- direct inversion or
- data assimilation approach.

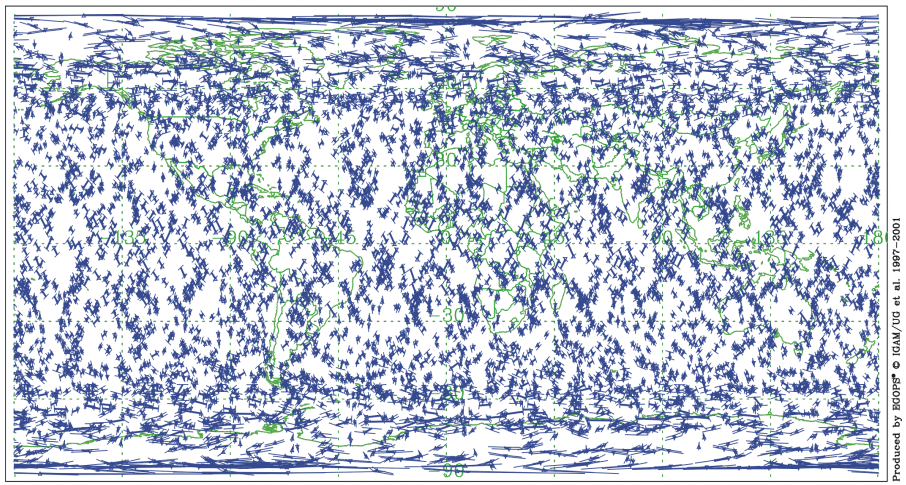
ACE+ Constellation of Satellites: Coverage

ACE+ LEO-LEO Occultation Events – Global Coverage in 30 Days



Number of Occ. Events (∇Set+ΔRise,LEO): 6928 total, 3464 setting, 3464 rising.

ACE+ GNSS-LEO Occultation Events – Global Coverage in 1 Day



No. of Occ. Events (∇Set+ΔRise,GPS+GAL): 5024 total, 2517 setting, 2507 rising.

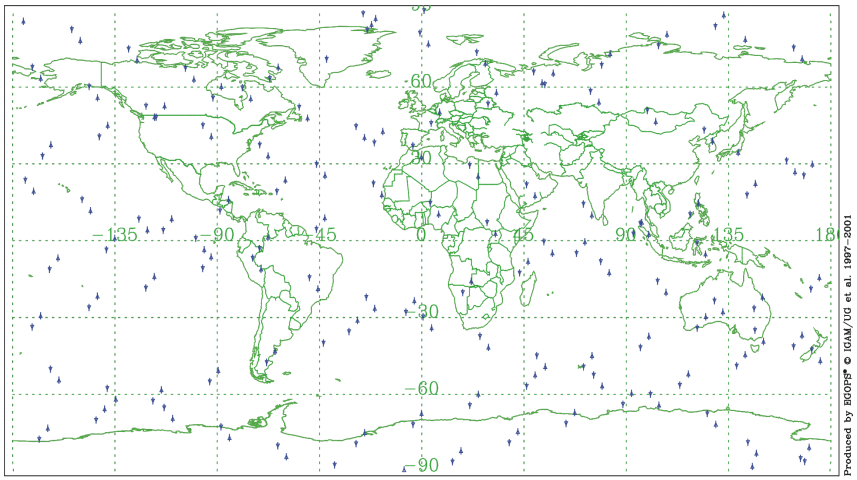
LEO-LEO occultation coverage amounts to ~7000 events/month

GNSS-LEO occultation coverage amounts to ~5000 events/day

(2Rx+2Tx ACE+ polar-orbiting LEO satellites and 54 GNSS satellites; 24 GPS and 30 GALILEO)

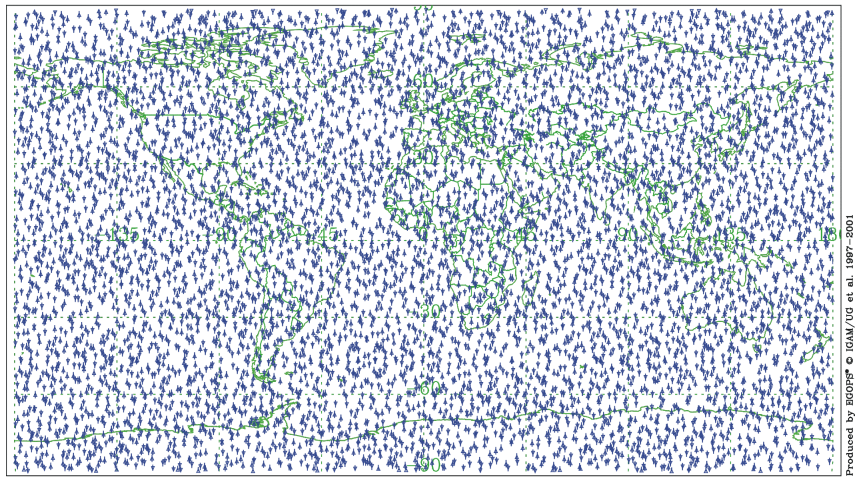
LEO-LEO Coverage per Day & per Month

ACE+ LEO-LEO Occultation Events – Global Coverage in 1 Day



Number of Occ. Events (∇Set+ΔRise,LEO): 230 total, 115 setting, 115 rising.

ACE+ LEO-LEO Occultation Events – Global Coverage in 30 Days

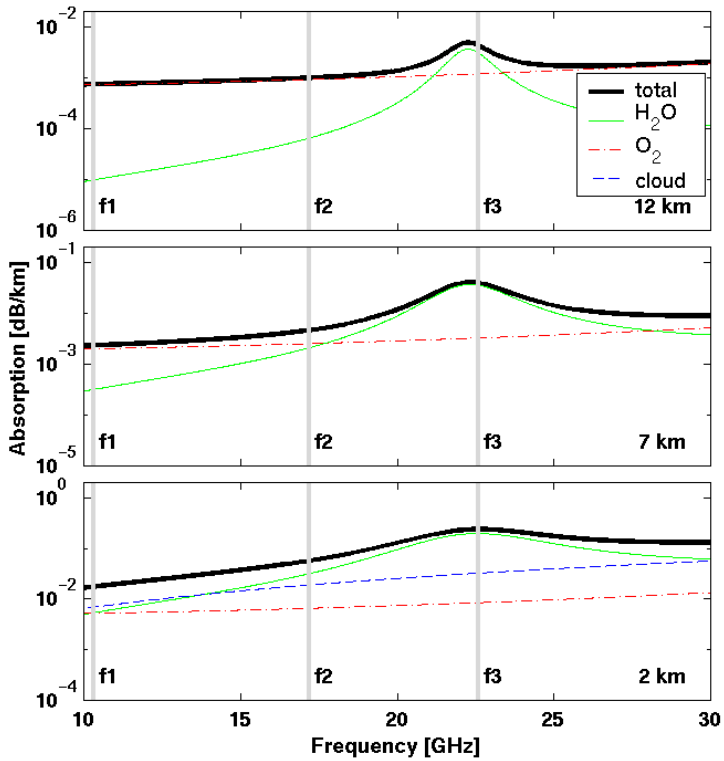


Number of Occ. Events (∇Set+ΔRise,LEO): 6928 total, 3464 setting, 3464 rising.

~230 LEO-LEO occultation events/day ~7000 LEO-LEO occultation events/mon

(2Rx+2Tx ACE+ polar-orbiting LEO satellites)

LEO-LEO Observation Performance (1)



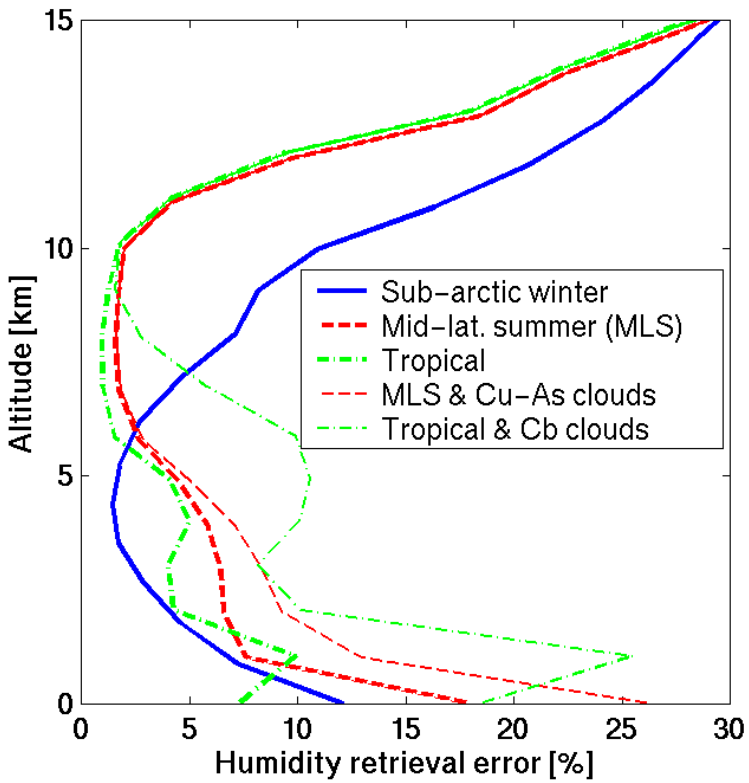
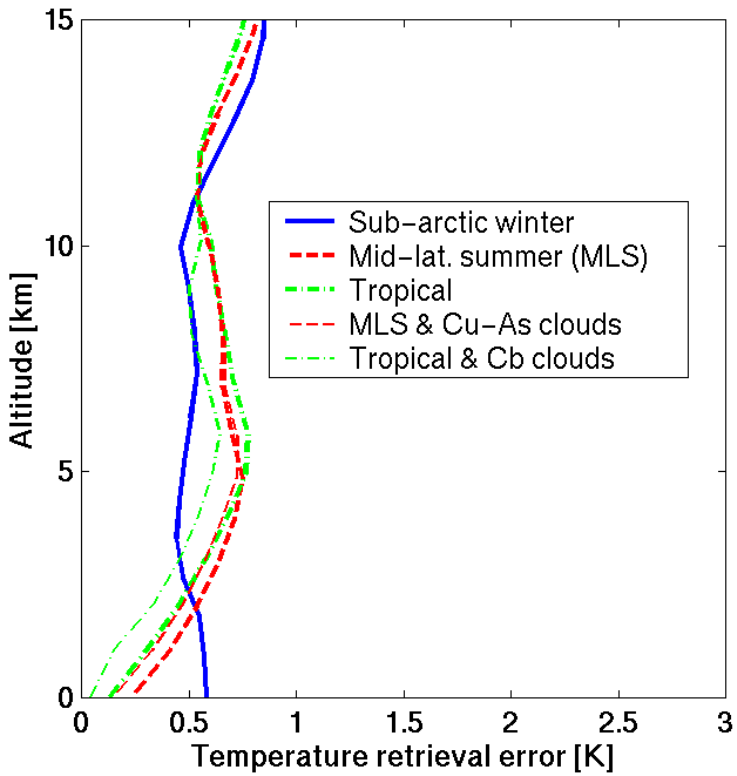


Illustration of absorption properties and humidity retrieval performance for LEO-LEO occultations (realistic sensor errors, moderate cloudiness, no horizontal variability)

LEO-LEO Observation Performance (2)



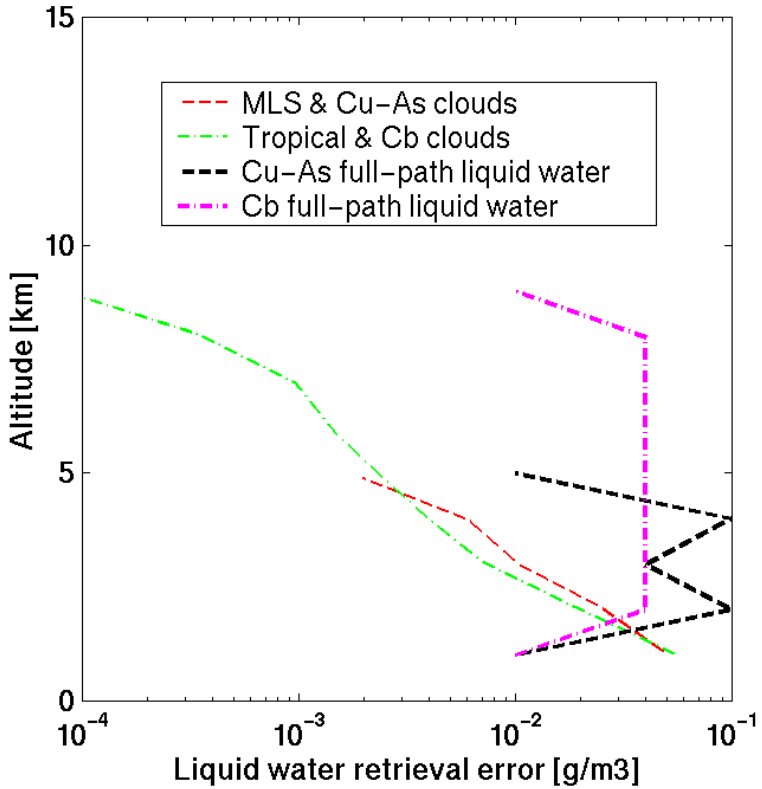


Illustration of temperature and liquid water retrieval performance for LEO-LEO occultations (realistic sensor errors, moderate cloudiness, no horiz. variability)

GNSS-LEO Observation Performance

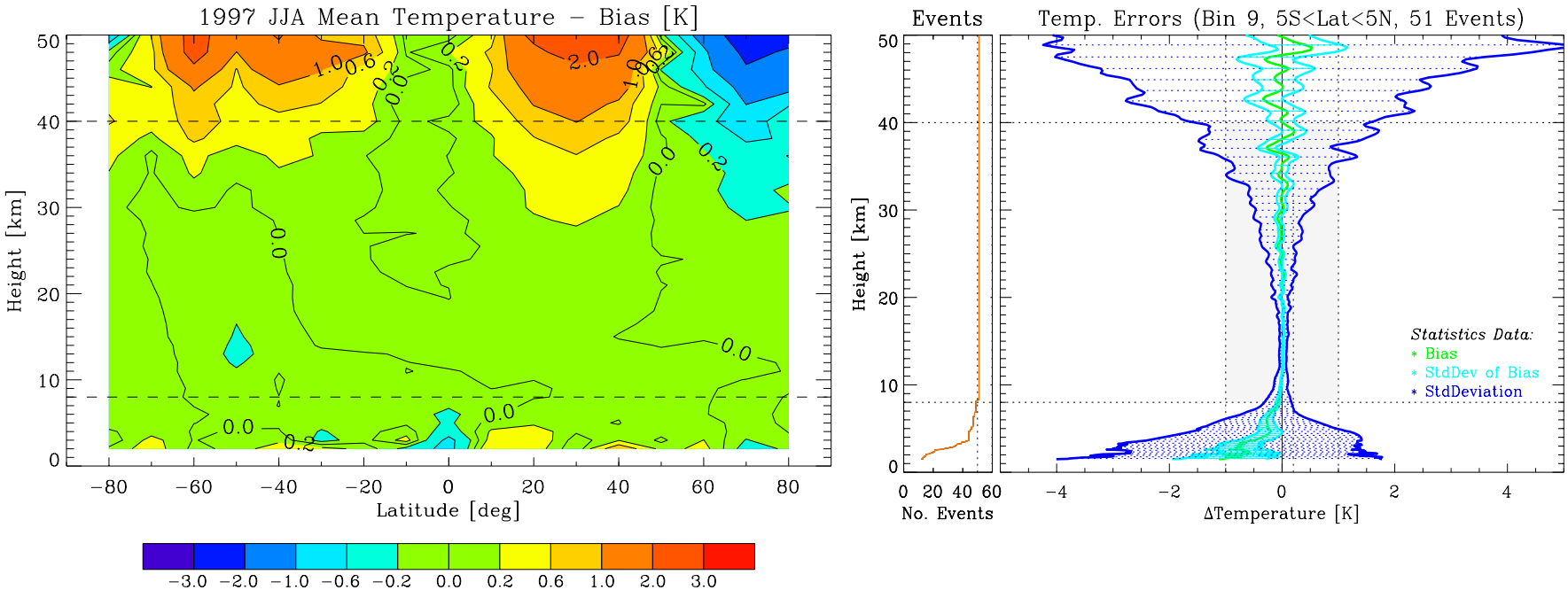


Illustration of retrieval performance using GNSS-LEO occultation data (realistic end-to-end simulations; *left:* lat-height slice of temperature errors of ~50 profile mean, *right:* vertical error structure at equator)

GNSS-LEO Observation Performance [older]

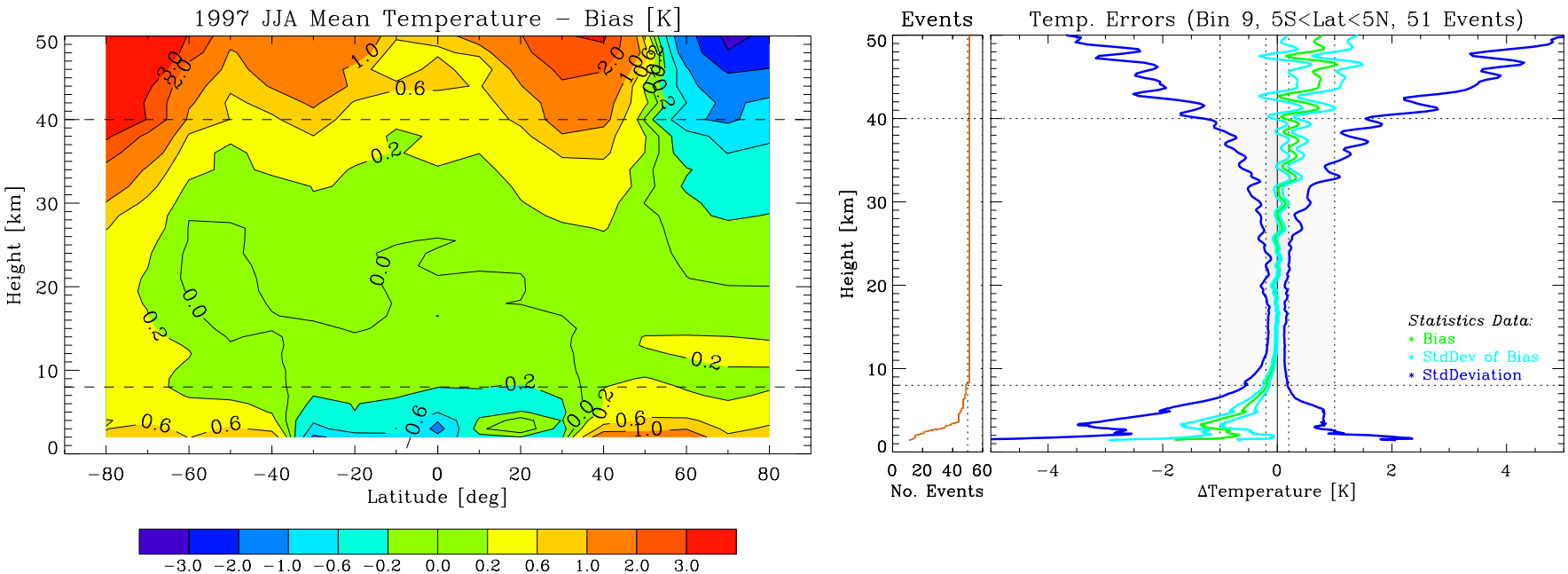


Illustration of retrieval performance using GNSS-LEO occultation data (realistic end-to-end simulations; *left:* lat-height slice of temperature errors of ~50 profile mean, *right:* vertical error structure at equator)

ACE+ Main System Requirements

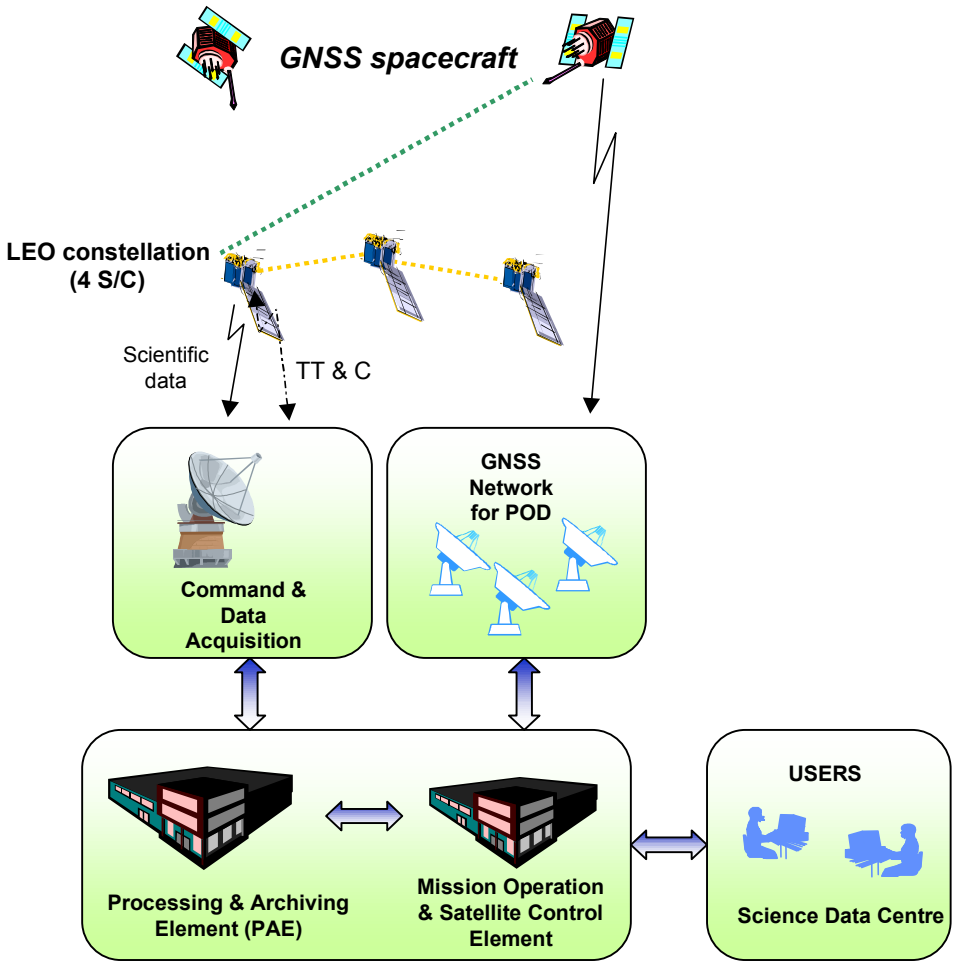
		LEO - LEO	GNSS - LEO
Horizontal domain		global	
Number of profiles / day		> 230	> 4400
Vertical domain		surface to 80 km for bending angle and transmission	surface to 80 km for bending angle and transmission
Vertical sampling		1 kHz (z < 20 km) 50 Hz (z > 20 km)	100 Hz (z < 20 km) 50 Hz (z > 20 km)
Time sampling		< 24 hrs	< 12 hrs
Bending angle accuracy (RMS)		Max{ 0.5 μrad , 0.2% }	Max{ 1 μrad , 0.4% }
Transmission accuracy (RMS)		Min{ 0.001 , 0.5% } @ 1Hz	2% @ 1 Hz
Transmission vertical stability	**linear drift** **2nd order drift** **sinusoidal var.**	< 0.01 dB over 15 sec [1)] < 0.001 dB/sec over 15 sec [1)] < 0.001 dB/sec over 1-15 sec	< 0.2 dB over 30 sec [1)] < 0.01 dB/sec over 30 sec [1)] < 0.01 dB/sec over 1-30 sec
Timeliness		< 30 days (for climate), < 3 hrs (for NWP) [2)]	
Temporal sampling		sample all local times within as small as possible time period	
Spatial distribution		homogeneously distributed events globally	

(derived from observation requirements on humidity and temperature)

1) Assumed relative to starting time corresponding to z = 15 km

2) On best effort basis (for a significant fraction of the data)

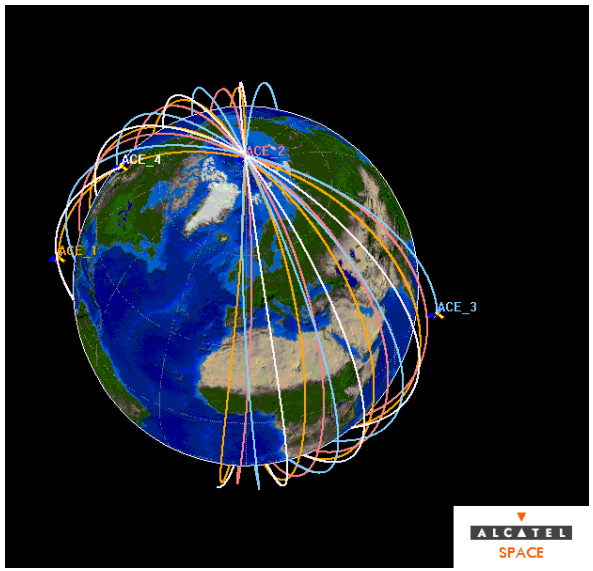
ACE+ Generic System Concept



The system requirements lead to a system concept including:

- a constellation of 4 small satellites
- 2 instruments on each satellite:
  - A GNSS receiver to observe occultations of GPS and GALILEO (GNSS) signals
  - A LEO-LEO Rx (on 2 sats) or Tx (on 2 sats) instrument for observing LEO-crosslink occultations
- receiving ground station(s) at high latitudes (e.g., Kiruna) and GNSS ground station network for POD
- ground segment (data processing, archiving, and distribution)

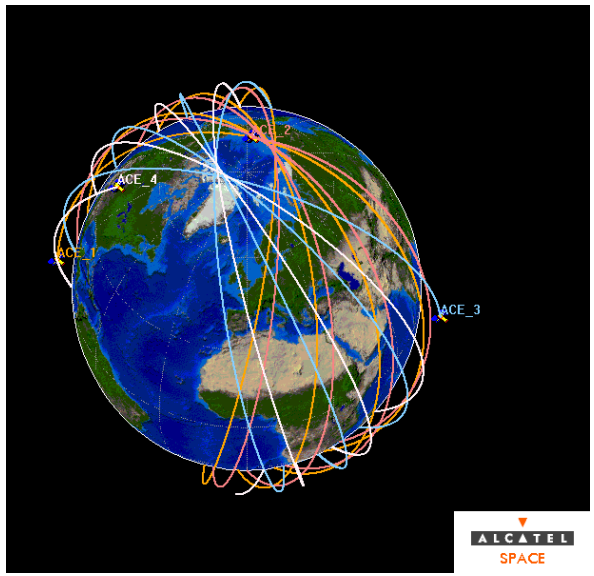
ACE+ Constellation Concepts



Concept 1:

– 2 orbital planes, counter-rotating sats
– 2 micro-satellites/plane
– polar inclination (i = 90°)
– 2 altitudes (~650 & 850 km)
– antenna FOV: +/– 7° in azimuth

best LEO-LEO performance/link budget

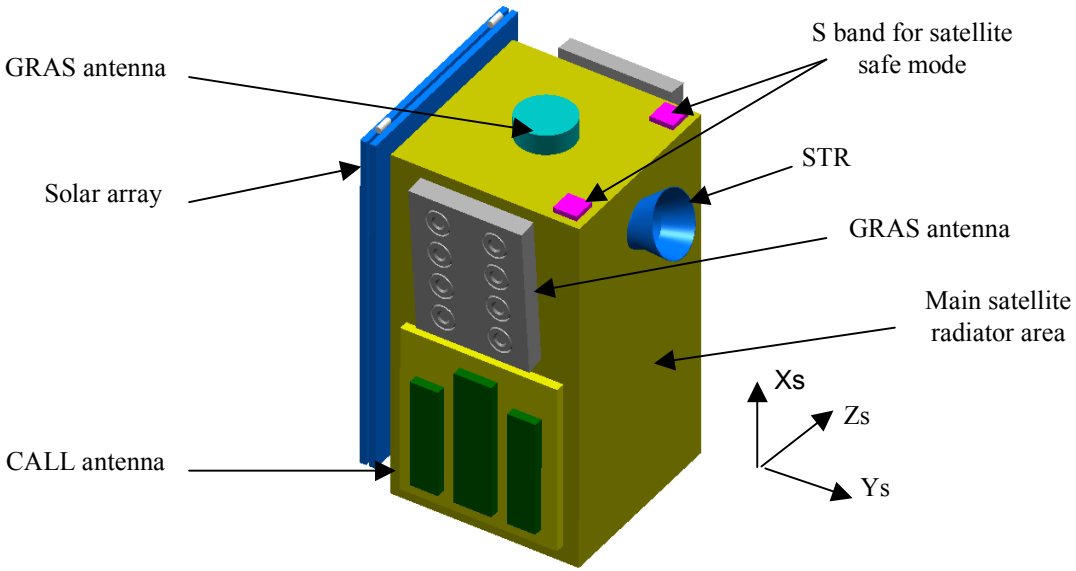


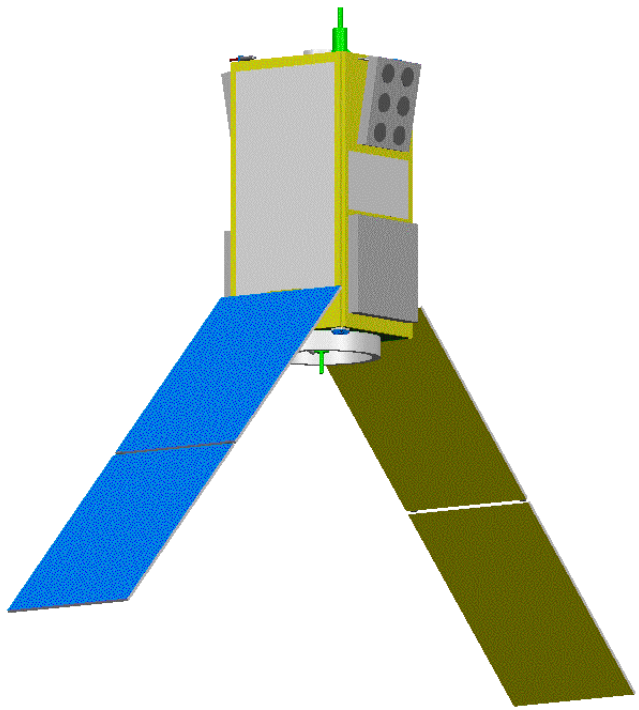
Concept 2:

– also 2 orbital planes
– 2 satellites/plane, sun-synchronous (i ~ 98°)
– also opposite nodal crossing (counter-rotating)
– 2 altitudes (~650 & 850 km)
– antenna FOV: +/– 25° in azimuth

may be favorable in terms of cost (due to sun-sync)

ACE+ Exemplary Satellite Concept





Mass Budget Example [kg]

Payload	18
Platform	90
Margins 10%	11
Total dry mass	119
Fuel	6
Total launch mass	125

Power Budget Example [W]

Payload	37
Platform	38
Margins	5
Total	80

The ACE+ Case
3. The Essence

1. Setting the Scene
    - Primary Issue of Concern
2. The ACE+ Mission
    - Goals and Objectives
    - Observation Requirements
    - Limitations of other Data
    - Measurement Methodology
    - Observation Performance
    - Draft System Concept
3. **The Essence**
    - **Unique Contributions of ACE+**
4. ACE+ Evaluation and Next Steps

Unique Contributions to the Science Goals and Objectives Thanks to Unique Characteristics

- High absolute accuracy of humidity and temperature for climate applications due to intrinsic self-calibration of occultation data:
  - humidity profiles from attenuation profiles (normalised intensity)
  - temperature profiles from Doppler shift profiles (time standard)
- High vertical resolution of fine structures in the atmosphere such as around the tropopause or near the top of the boundary layer.
- All-weather capability due to long wavelengths (> 1 cm).
- Global and even coverage, over both oceans and land.
- Dense array of measurements from the ACE+ constellation of satellites, allowing climate monitoring even at regional scales.
- Rigorous separate measurement of humidity, temperature, and pressure in the troposphere by the LEO-LEO occultations.

"The good method is like a sack (bag): it retains everything. The better method is like a sieve (filter): it only retains what matters."

(after Hellmut Walters)

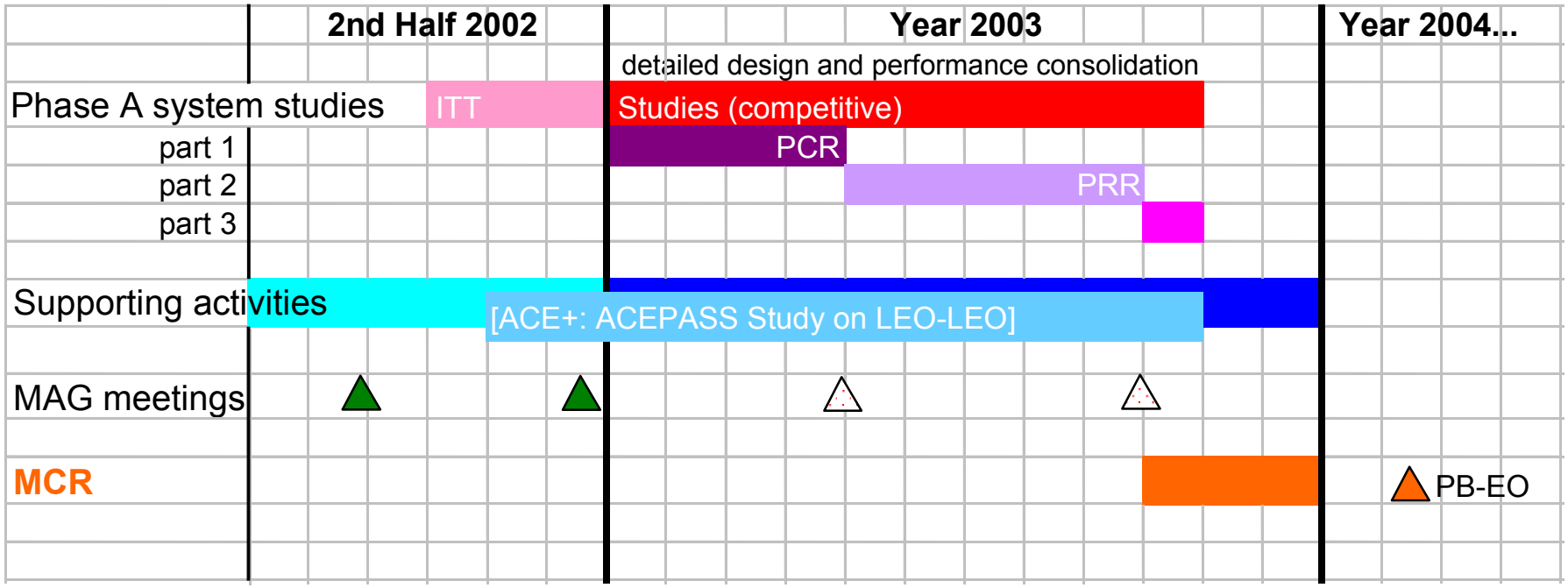
Deutsches Originalzitat (Hellmut Walters):
„Das gute Gedächtnis ist wie ein Sack:
es behält alles.
Das bessere Gedächtnis ist wie ein Sieb:
es behält nur, worauf es ankommt."

From the Panels & ESAC Assessment on ACE+

- Adequate balance between continuity (GNSS-LEO L-band occultation) and innovation (LEO-LEO X/K-band occultation).
- First mission employing the novel LEO-LEO occultation for *q* and *T* profiling and including GALILEO-LEO occultation.
- A major asset is the absolute calibration of refractivity over mission lifetime: essential for climate change studies.
- Potential for long time series and to create reference climatologies: very timely (ESAC: "...could give Europe the lead in precise monitoring of global climate").
- Selected as top-priority of three missions recommended for phase A study (1. ACE+, 2. EGPM, 3. SWARM).
- Financially at the limit of Opportunity Missions: efforts on cost needed.

ACE+ …Next Steps
2002 – 2003 Schedule

Next Steps in Mission Consolidation



PCR = Preliminary Concept Review; PRR = Preliminary Requirements Review; MCR = Mission Confirmation Review, MAG = Mission Advisory Group

- **at the end of Phase A missions will be subject to MCR, including scientific and technical/programmatic review.**
- **after MCR the ESA PB-EO will decide, upon proposal by the ESA Executive, on the mission to be implemented as the 3rd EEOM (nominally the top-ranked ACE+).**
- **activities, including search for implementation possibilities, will continue on the other candidate missions until a new EEOM cycle is started.**

ACE+ Science Team Building

Reminder: **ACE+ is an ESA Mission**

Lead Investigators: **Principal scientific advisers to ESA on ACE+ and leaders of scientific preparation and exploitation activities**

ACE+ MAG (Mission Advisory Group): **Formal ESA scientific advisory body; in phase A: ESA convener Tobias Wehr, members besides Per and Gottfried: S. Buehler (Ger), K. Craig (UK), G. Elgered (S), H. LeTreut (F), L. Kornblueh (A)**

ACE+ IST (International Science Team): **Informal body doing the actual scientific preparation (2004-2007) and exploitation (2007-2012) work on ACE+;**

initial steps:

- **Notification-of-Interest form (importing heritage from proposal member team) [OPAC-1]**
- **Screening and acceptance of ACE+ IST NoI forms (incl. proposal heritage) [Oct-Nov 02]**
- **Acceptance as provisional ACE+ IST member (and associated members) [Nov-Dec 02]**
- **ACE+ IST e-mail list and IST-wide distribution of NoIs Summary Report [Dec 02]**
- **Keep IST informed about progress, opportunities, etc. [> Dec 02]**
- **prov2firm status after confirmation of ACE+ for full implementation [early 2004]**

ACE+ ...Next Steps

Let's realize it. - Thank You!