Integrated Approach to Precise GPS/LEO Orbit Determination in Support of GPS Meteorology

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Presentation Overview

- GPS meteorology: definition and problem statement
- Land-based GPS meteorology
- Space borne GPS meteorology
- How can GPS contribute to weather forecasting? Is it really important?
- What do we need to do to make GPS meteorology truly operational?
- The OSU approach to orbit determination
- Closing remarks

Underlying Problem

- Two key variables in the study of global change processes are global atmospheric temperature and moisture distribution

Water vapor plays a crucial role in dynamics and thermodynamics of many atmospheric processes that act over a wide range of temporal and spatial scales, covering the global hydrologic and energy cycles that effectively define the local and global climate change

- Recovery of temperature, pressure and water vapor profiles

Underlying Problem

Problems: (1) scarcity of traditional meteorological observations, especially over the Southern Ocean and Polar Regions, (2) shortcomings of the traditional methods over the land

Consequences: uncertainties in a global and regional weather analysis → hinder the progress in climate change research and weather prediction

Needed: improvement in the methods of measuring 3D distribution of water vapor with high spatial and temporal resolution on a global scale is critically needed for the potential improvement of regional-scale weather forecasting and analysis, and climate modeling.

What is GPS Meteorology?

- **Radio signals traversing the atmosphere are affected by radio refraction due to water molecules along the ray path, causing a delay, usually referred to as the wet path delay**

$$\Phi^{kl}_{ij,1} = \rho^{kl}_{ij} - \frac{I^{kl}_{ij}}{f_1^{2}} + T^{kl}_{ij} + \lambda_1 N^{kl}_{ij,1} + m^{kl}_{ji,1} + \varepsilon^{kl}_{ij,1}$$

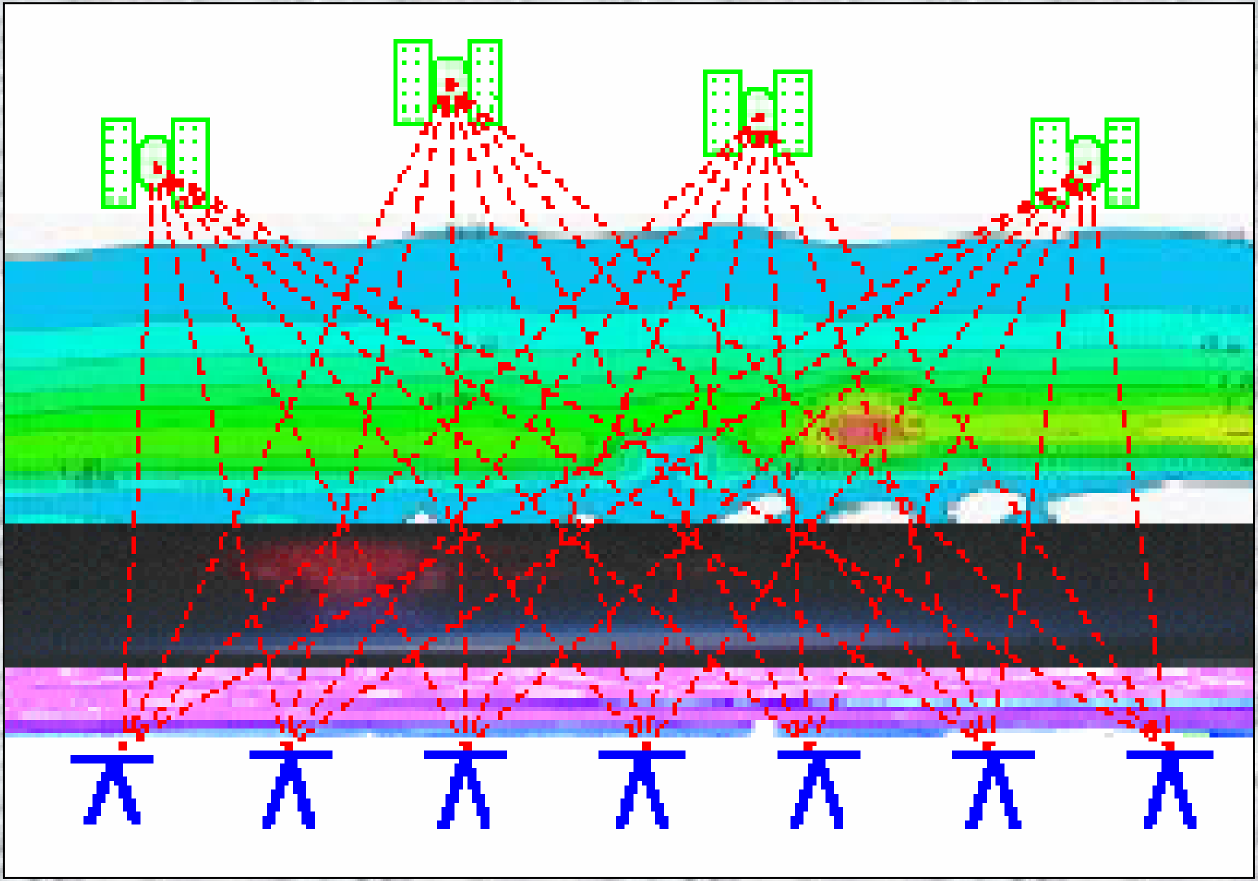
- **In the double difference equation above, the term T accounts for both, so called wet and dry tropospheric path delay**

What is GPS Meteorology?

- Numerous studies have shown that a local/regional network of ground GPS receivers, located at known positions and collecting phase measurements simultaneously, is able to provide integrated precipitable water vapor (PWV) with accuracy of 1-2 mm, from the estimates of the tropospheric path delays

- GPS orbits must be precisely known and meteorological data must be observed at every station [see Borbas, 1998; Johasson et al, 1998; Kruse et al., 1999; Ware et al., 2000]

Atmospheric Sensing with Ground-based GPS Receivers



What is GPS Meteorology?

- So, if PWV (or, in other words, atmospheric data) can be retrieved from GPS observable, this information can be fed to the atmospheric models (such as MM5) used in weather forecasting and climate modeling, facilitating the GPS meteorology

- Naturally, operational weather forecasting requires real or near real-time (2-3 hour delay) PWV data availability (data assimilation delay accepted by the World Meteorological Observation)

- For this to happen (with a sufficient accuracy), several important aspects must be addressed, as will be explained later in this talk

GPS Meteorology: Operational Aspects

- In order to retrieve PWV, the contribution of the dry air is removed from the estimated total delay, using the measured ground air pressure

- Combination of dual frequency signal is routinely used to remove the ionopheric delay from the GPS observable

- Differential GPS technique is applied in order to cancel variations of the clock oscillators

GPS Meteorology: Operational Aspects

- In a multi-station analysis, tropospheric delay parameters can be estimated at regular time intervals (15-30 min) for each receiver, and converted to PWV as shown by [Krause et al., 1999]

- Moreover, the introduction of long baselines (minimum 500 km) decorrelates the estimated tropospheric parameters within the network, allowing for absolute estimation of wet delay [Duan, et al., 1996; Borbas, 1998].

Ground Based GPS Meteorology

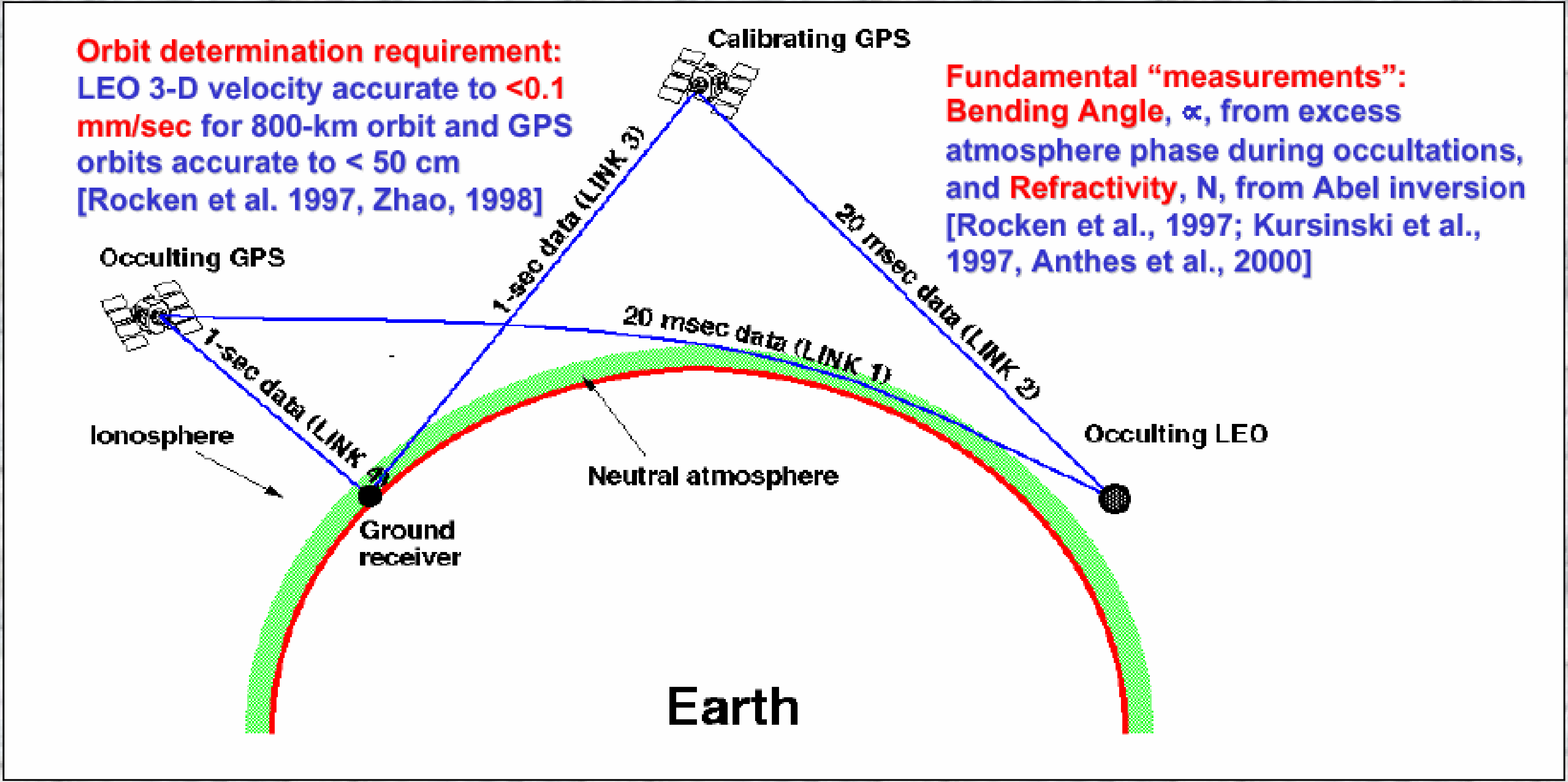
- Ground based network of GPS receivers offers autonomous, portable, all-weather and economic solution, providing continuous PW estimates (every 15 to 30 minutes) with higher than radiosondes temporal and spatial resolution, practically unaffected by clouds, precipitation and aerosol content in the atmosphere.
- Consequently, ground-based GPS technique could become an important source of PW for operational numerical weather prediction (NWP), if near-real time POD (precise orbit determination) for GPS, as well as fast data assimilation techniques into atmospheric models were developed [Kuo et al, 1996].

Space Borne GPS Meteorology

- Recent study has proved that the GPS receiver aboard a microsatelite in a low Earth orbit (LEO), supported by a ground-based network of receivers can be used to determine the atmospheric refractive index (and consequently PWV) as a function of altitude during the event of satellite occultation by the Earth atmosphere [Melbourne et al., 1994, Kursinski et al, 1997; Rocken et al., 1997]

- GPS phase measurements as they are occulted by Earth's atmosphere could provide atmospheric refractivity soundings and thus yield information on global atmospheric temperature, humidity and ionospheric structure

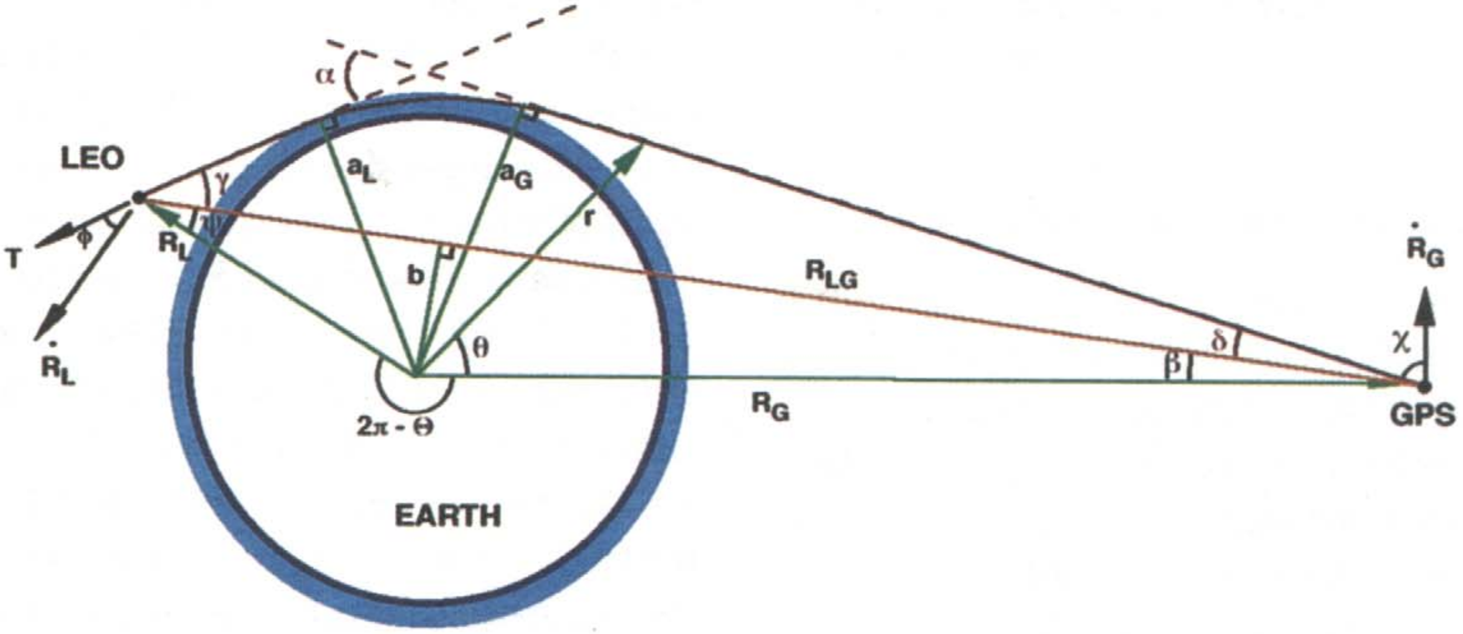
Occultation Technique of WV Retrieval



Orbit determination requirement: LEO 3-D velocity accurate to <0.1 mm/sec for 800-km orbit and GPS orbits accurate to < 50 cm [Rocken et al. 1997, Zhao, 1998]

Fundamental "measurements": Bending Angle, ∝, from excess atmosphere phase during occultations, and Refractivity, N, from Abel inversion [Rocken et al., 1997; Kursinski et al., 1997, Anthes et al., 2000]

Occultation Technique: Observation Geometry



GPS/MET Pilot Project

- The University Corporation for Atmospheric Research (UCAR) GPS/MET (GPS/Meteorology)
  - ~730 km orbit, launched in 1995
  - provided the first proof-of-concept demonstration for the potential of an all-weather measurement system for the atmospheric temperature, pressure and humidity profiles
  - global scale
  - unprecedented temporal and spatial resolution and accuracy [Ware et al., 1996; Kursinski et al., 1997; Rocken et al., 1997]

GPS/MET Pilot Project

- GPS/MET radio occultation observations of GPS were used to derive refractivity, pressure, and temperature in the stratosphere and upper troposphere, and refractivity, density, pressure and water vapor pressure in the lower troposphere, as well as vertical profiles of electron density in the ionosphere.

Space Borne GPS Meteorology

- The availability of remote sensing observations from GPS radio occultation sensors provides a unique opportunity to improve the quality of regional meteorological analysis,
    - particularly over the traditionally under-sampled regions, if a sufficient number of sensors is launched and supported by an adequate ground based tracking network.

Current space missions:

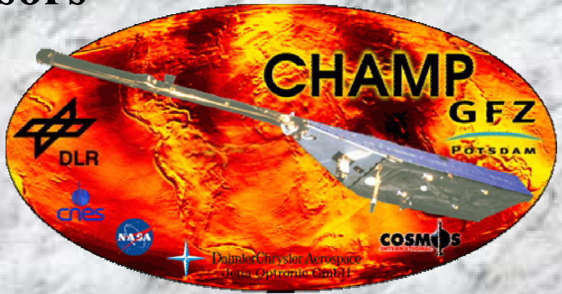
Danish ORSTED – altitude 655 to 857 km
South African SUNSAT – altitude 400 to 830 km
German CHAMP – altitude 454 km and lower
International SAC-C – altitude 702 km (stable)

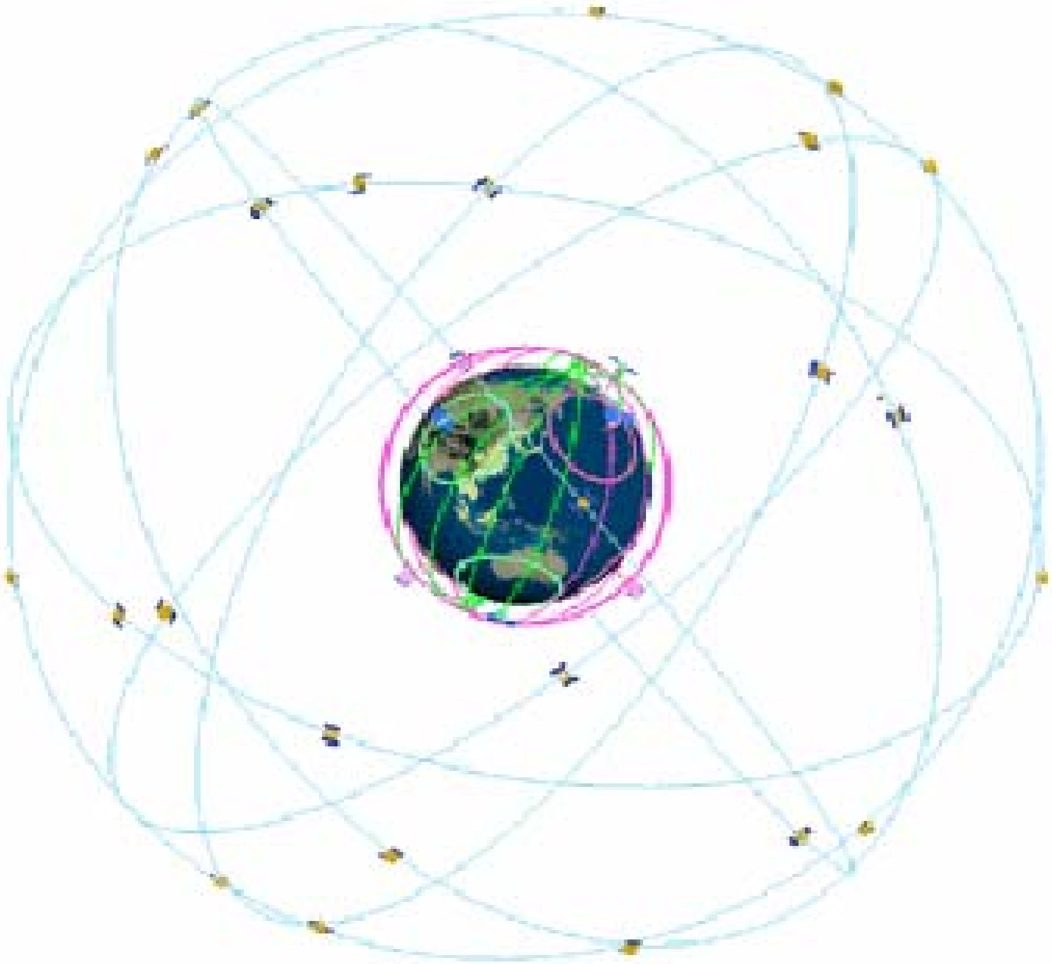
Upcoming space missions:

US GRACE (2 SV) – altitude 300 to 500 km (2001)
US/Taiwan COSMIC (6 SV) – altitude 400 to 800 km (2005)
European METOP – (2003), first in a planned series

Land-based networks:

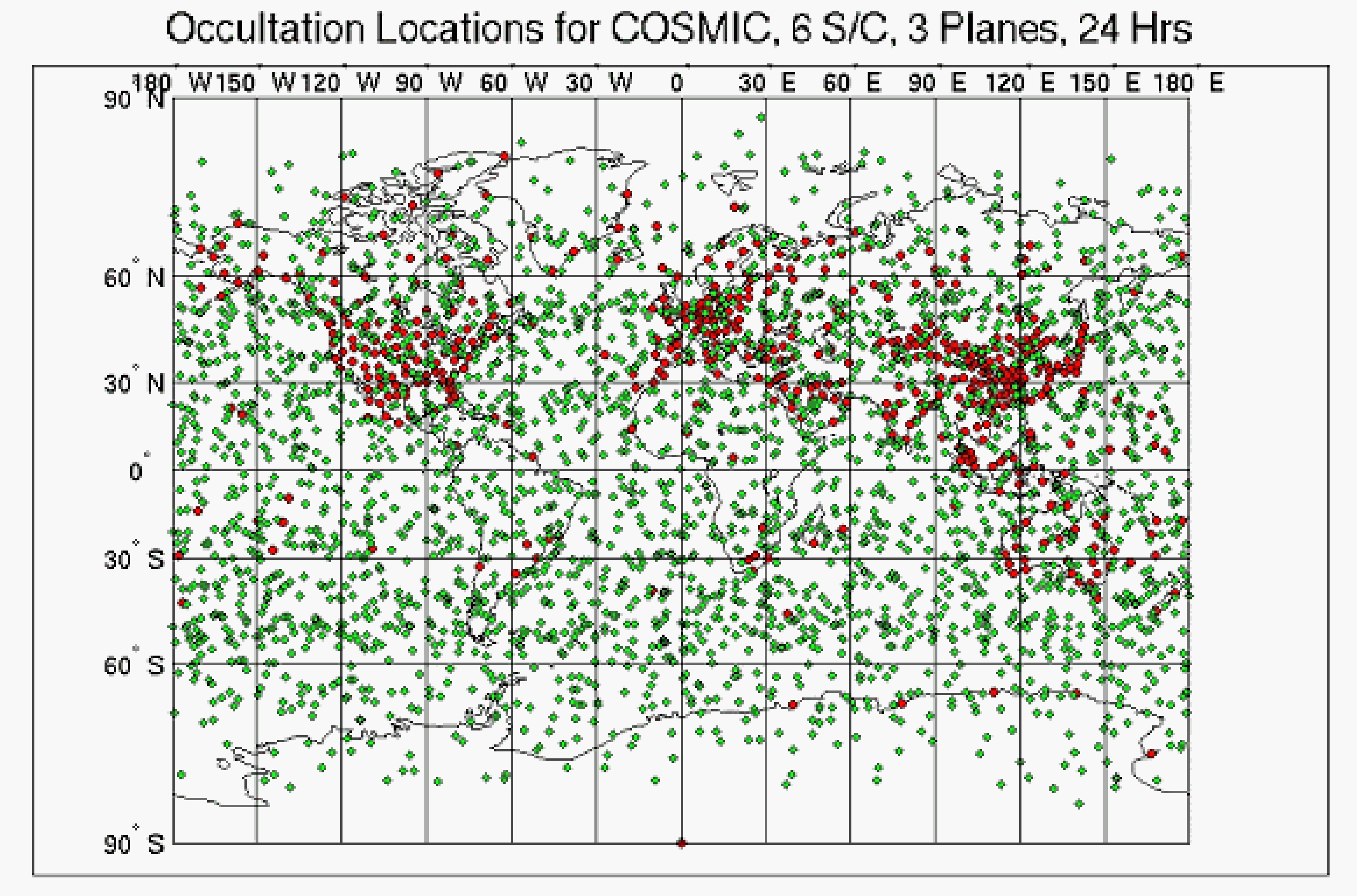
Existing IGS stations with meteorological sensors
Upcoming US SuomiNet – 200 – 300 stations





COSMIC and GPS Constellations

Typical daily COSMIC soundings (> 4000) are shown in green, location of radiosonde sites in red (source: UCAR)



Key Issue

Provided sufficient LEO constellation,

- Near real-time availability of quality GPS/LEO orbits is currently considered a primary limitation in operational GPS meteorology
  - Needed for the GPS radio occultation technique for a number of current and upcoming LEO missions
- International GPS Service (IGS) works towards providing the GPS rapid orbit within a few hours

Achievable Accuracy

- **Practical accuracy of GPS/MET is at ~30 cm level (or 0.3 mm/s) RMS, which combined with 10 cm GPS orbit error (precise post-processed IGS orbits) causes an error in temperature retrieval of ~1° K**

- **Predicted GPS orbit accuracy at (optimistically) 50 cm RMS level would cause an error of at least a few degrees Kelvin at altitudes of 30-60 km [Rocken et al, 1997; Kruse et al., 1999]**

- **The IGS rapid orbit, available with 12 hour latency, even though much better that the predicted one, still cannot meet the requirements of near real-time GPS meteorology.**

Requirements for Orbit Quality

- The World Meteorological Organization (WMO) recommends the accuracy of 1ºK for temperature profiles recovery
- For temperature retrieval accurate to ±1º K below 30 km knowledge of the excess phase delay time derivative to be < 1 mm/s is needed [Wickert et al. 2000]

Estimated Temperature Error [deg K] Induced by the Errors in GPS/LEO Orbits [Langley, 1999; Zhao, 1998]

LEO Altitude [km]	Orbit Accuracy [cm] Post-processed (few days to 2 weeks)	Orbit Accuracy [cm] Rapid Solution (1-2 days)	Orbit Accuracy [cm] Predicted
GPS LEO	5 <15	10 <30	50 <100
750	0.1° to 40 km 0.05° to 25 km	0.6° to 40 km 0.2° to 25 km	2.5° to 40 km 0.3° to 25 km
470	0.3° to 40 km 0.1° to 25 km	0.9° to 40 km 0.2° to 25 km	3.6° to 40 km 0.6° to 25 km

Problem Statement

- Numerous research institutions work on developing tools for rapid LEO orbit determination and dissemination

- The Ohio State University is currently pursuing an alternative approach to GPS/LEO POD (orbit determination), based on a fast and accurate
    - triple difference method, developed in 1995 by Brzezinska, Goad and Yang

- current research at OSU is sponsored by NASA Goddard Space Flight Center

Orbit Determination : The Concept

- **Orbit determination**: prediction/estimation of the satellite position and velocity vector based on the known force model (perturbations) acting on the satellite, and/or geometric constraints, i.e., the observations of the satellite path
  - GPS phase-range/pseudorange to GPS satellite
  - GPS phase-range/pseudorange measured by GPS receiver on board another satellite
  - Satellite Laser Ranging
  - Doppler effect, etc.

Orbit Determination: The Concept

$$\ddot{\vec{r}}(t) = -\frac{GM_E}{\left|\vec{r}(t)\right|^3}\vec{r}(t) + \vec{a}(t)$$

- The equations of motion can be solved analytically or numerically, if the force models are known (orbit prediction)
  - models are not perfect – observations are needed

- Implementing the knowledge about the factual measurements of the satellite's position constitutes the orbit improvement step
- Iterative process

Orbit Determination: Strategies

- **Dynamic**: Equations of motion are integrated in the prediction step based on selected force model and externally known initial position/velocity vectors
- Selected dynamic parameters of the model, including the initial position/velocity vectors, are corrected in the orbit improvement step

Orbit Determination: Strategies

- Dynamic method
  - Strongly depends on the dynamic (force) model used
  - Good for high satellites where force models are "smooth" and the most difficult to model forces (such as atmospheric drag, high degree/order components of gravity field) are not present
  - Is usually followed by the orbit improvement step (factual measurements of the satellite position are used)
  - Initial position and velocity vectors, solar radiation pressure scaling factor, Earth Rotation Parameters (ERP, rate of rotation, polar motion), etc., are estimated

Kinematic: The initial orbit determination (prediction) may be the same as the dynamic case, and is needed as an approximation to form a system of observation equations to perform the least squares adjustment based on observable of the satellite positions

- Good for low LEO POD (long range kinematic GPS)
- The dynamic constraints in the estimation step are totally removed (simple)
- Does not depend on dynamics but depends on quality of GPS orbits
- Must have strong geometry for high accuracy, i.e., LEO with a GPS receiver on board must see 7 or more GPS satellites in good geometry

Orbit Determination: Strategies

- **Hybrid**: Weighted dynamics in the estimation procedure
  - If more weight is put on dynamic information, it reduces to the dynamic solution
  - If more weight is put on geometry/observable, it reduces to kinematic solution
  - Both cases are balanced within the solution, depending on the strength and geometry of the observable
  - Most versatile approach, allows for taking the best from both methods

GPS POD: Current Approaches

- IGS Centers use either un-differenced phase or double differenced phase observable from a large network of ground based receiver
- Virtually identical dynamics model is used
- OSU developed a triple-difference based approach in 1995 [Brzezinska, Goad, Yang]
- Quality of IGS solution is at ~10 cm level
- OSU solution compares within 10-15 cm RMS with IGS solution, but is much faster and implemented on a PC (portability w.r.t to a work station!)

Why Triple Differences?

$$\Phi^{k}_{i,1} = \rho^{k}_{i} - \frac{I^{k}_{i}}{f_1^{2}} + T^{k}_{i} + \lambda_1 N^{k}_{i,1} + c(dt_i - dt^{k}) + \lambda_1\left(\varphi^{k}_{0} - \varphi_{i_0}\right) + m^{k}_{i,1} + \varepsilon^{k}_{i,1}$$

$$\Phi^{k}_{i,2} = \rho^{k}_{i} - \frac{I^{k}_{i}}{f_2^{2}} + T^{k}_{i} + \lambda_2 N^{k}_{i,2} + c(dt_i - dt^{k}) + b_{i,1} + \lambda_2\left(\varphi^{k}_{0} - \varphi_{i_0}\right) + m^{k}_{i,2} + \varepsilon^{k}_{i,2}$$

$$\Phi^{kl}_{ij,1} = \rho^{kl}_{ij} - \frac{I^{kl}_{ij}}{f_1^{2}} + T^{kl}_{ij} + \lambda_1 N^{kl}_{ij,1} + m^{kl}_{ji,1} + \varepsilon^{kl}_{ij,1}$$

Double difference

Differencing two double differences, separated by the time interval *dt* provides triple-differenced measurement, that effectively cancels the phase ambiguity biases, N_1 and N_2

$$\Phi^{kl}_{ij,1,dt} = \rho^{kl}_{ij,dt} - \frac{I^{kl}_{ij,dt}}{f_1^{2}} + T^{kl}_{ij,dt} + m^{kl}_{ji,1,dt} + \varepsilon^{kl}_{ij,1,dt}$$

Iono-free Triple Difference

$$\Phi_{ij,iono-free,dt}^{kl} = \rho_{ij,dt}^{kl} + T_{ij,dt}^{kl} + \alpha_1 \varepsilon_{ij,1,dt}^{kl} + \alpha_2 \varepsilon_{ij,2,dt}^{kl}$$

Linear combination of triple difference observable on L1 and L2 frequencies leads to an optimal observable model where ionospheric effects are removed → best approach to handle POD as this process is controlled mainly by the long baselines

Why Triple Differences?

- **With about 170 IGS stations, the number of baselines to process is very large, thus the number of double difference integer ambiguities to fix is very large**
- **Ambiguity fixing step is very costly time-wise and for long baselines the level of success is rather low**
- **Consequently, most of double difference solutions is performed with floating ambiguities**
    - **Or fixing takes a substantial amount of time, precluding the method from near real-time implementation**
- **This prompted us to bring up triple difference approach**

Why Triple Differences?

- Schaffrin and Grafarend [1986] proved that elimination of nuisance parameters, such as ambiguities, from the Gauss-Markov model leads to the equivalent system, under the condition that covariance matrix for the reduced system is modeled properly
- Thus, double difference with float ambiguities and triple difference with no ambiguities at all, but with a full covariance matrix, offer equivalent solutions
- So, why bother with ambiguities at all? Use ionosphere free triple difference!

Why Triple Differences?

- Unknown ambiguities are fully eliminated, thus, the size of the system of normal equations is dramatically decreased, so is the processing time, with virtually no degradation to the solution quality
- Allows for completely automated data processing without the overhead of working with very large normal matrices or cycle-slip fixing
- **Price to pay**: complex covariance matrix (correlation)
- **Remedy**: fast Cholesky factorization scheme to decorrelate the observable

OSU Triple Difference Solution

The combined processing time on Pentium 90 MHz, using 32-hour data span from 40 IGS stations, is below 4 hours [Brzezinska, 1995; Kwon, 1997]. Just by using faster processor, it is safe to expect that this time could be reduced to about 1 hour (again, for the entire GPS constellation over 32-hour arc, even if more stations are used), promising already a near-real time POD. Moreover, the internal procedures could still be modified to further optimize the processing time → our current focus

- Algorithmic concept and its implementation presented above indicate that triple difference approach should be capable of near real-time POD for GPS, and could also provide an attractive kinematic alternative for LEO POD, while assuring the same level of accuracy as provided by the post processed orbits.

- If the real-time data were transmitted by the observing stations in batches of one to two hours, an optimal batched least squares algorithm could provide a sequential solution and store the normal equations for each processed time interval, and stack the entire sequence for 24-32 hour final solution (post-processed), assuring the continuity between the subsequent batches of data.

- This approach to real-time POD is now extensively studied

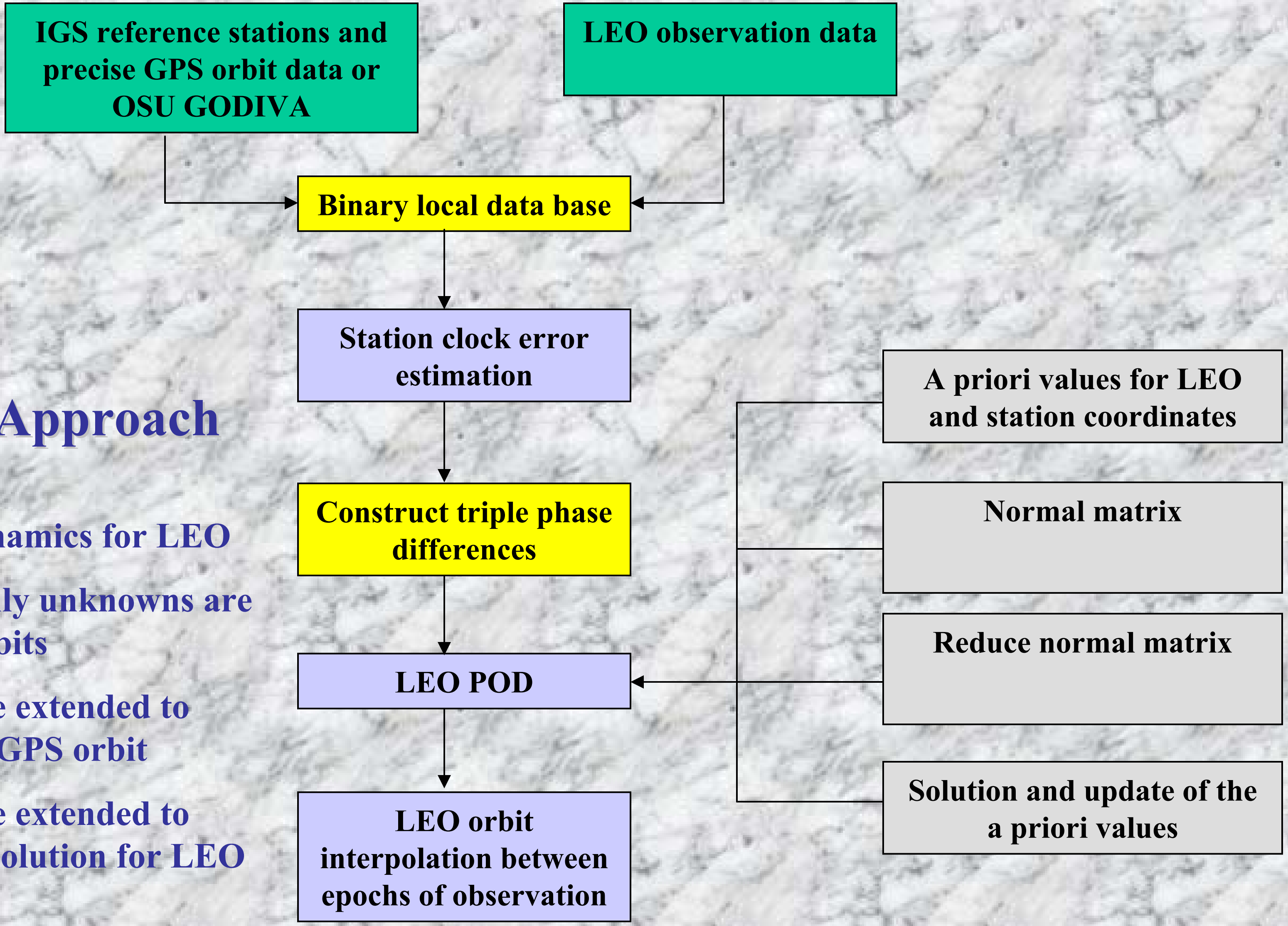
Kinematic Approach: Existing Solutions

- **Kinematic GPS POD and Kinematic vs. Dynamic POD for TOPEX/Poseidon [Courtney, 1999; Byun & Shutz, 1998]**
  - **Triple differenced phases used for initial orbits**
  - **Double differenced phases with fixed ambiguities used in the final solution**
  - **5-6 cm difference between the orbits from the two methods over a 2-hour arc solution.**
  - **Minimum of seven satellites are required for quality kinematic POD**

- **A posteriori tracking of LEO with GPS [Bisnath & Langley, 1999]**
  - **Triple differenced codes/phases; simulation for Canadian BOLAS (Bistatic Observations with Low Altitude Satellites)**
  - **Suggest better than 15 cm 3D RMS could be obtained with best GPS orbits from IGS**

OSU Approach

- No dynamics for LEO
- The only unknowns are LEO orbits
- Will be extended to include GPS orbit
- Will be extended to hybrid solution for LEO



IGS reference stations and precise GPS orbit data or OSU GODIVA

LEO observation data

Binary local data base

Station clock error estimation

Construct triple phase differences

LEO POD

LEO orbit interpolation between epochs of observation

A priori values for LEO and station coordinates

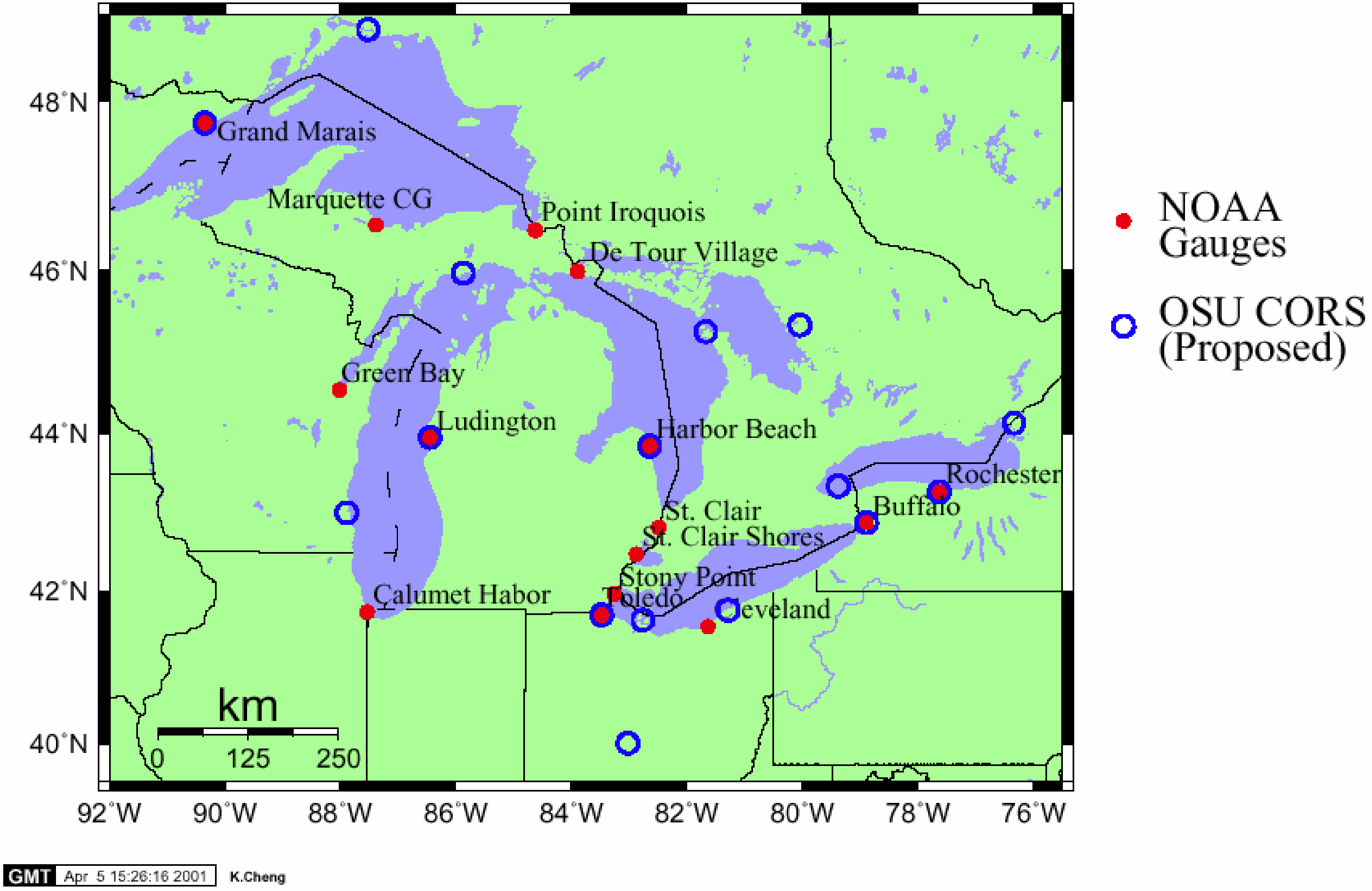
Normal matrix

Reduce normal matrix

Solution and update of the a priori values

Ultimate Objectives

- GPS/LEO POD with target accuracy of 10-20 cm and <30 cm respectively, is expected to support occultation data retrieval
- It is anticipated that occultation data, combined with the ground-based atmospheric data, will establish a near-real time atmospheric profile retrieval system in the Great Lakes region
- The Ohio State University Great Lakes SuomiNet GPS network is planned to be installed within 2001-2002 [Shum, Conner, Brzezinska, Kwon, Hazelton, and others]
- This network is planned to be a “test-bed” for atmospheric, geodynamic and geodetic research and operational applications with other partners
- Ultimate goal is to collaborate with Great Lakes Forecasting/Nowcasting research and operation centers to study potential enhancements using the data from this network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● NOAA Gauges
○ OSU CORS (Proposed)
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Thank you!