The Accomplishments of the IGS and their Implications on the Future of Geodesy

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Symposium

International GPS Service

10th Anniversary as an official IAG Service

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Motivation for the IGS in 1989

•The primary motivation in planning the IGS was the recognition in 1989 that the most demanding users of the GPS satellites, the geophysical community, were purchasing receivers in exceedingly large numbers and using them as more or less black boxes, using software packages which they did not completely understand, mainly for relative positioning.

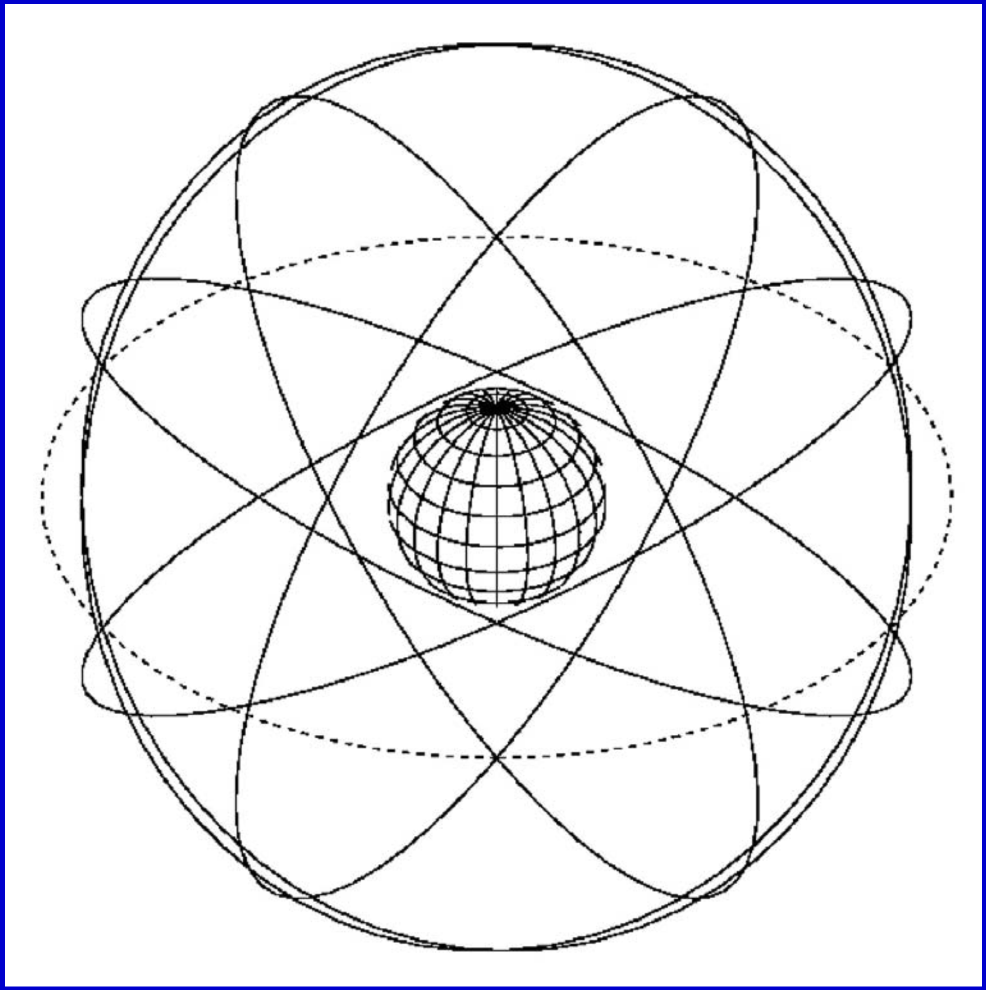
•The other motivation was the generation of precise ephemerides for the satellites together with by-products such as earth orientation parameters and GPS clock information.

Planning the IGS 1989-1991

Date	**Event**
August 1989	IAG Scientific Assembly in Edinburgh. Plans by Mueller, Mader, Melbourne, Minster, and Neilan
March 1990	IAG Executive Committee Meeting in Paris decides to establish a Working Group to explore the feasibility of an IGS under IAG auspices. I.I. Mueller was elected as chairman.
April 1990	The Working Group is redesignated as *IAG Planning Committee for the IGS* in Paris
September 1990	Planning Committee Meeting in Ottawa. Preparation of the *Call for Participati*on
February 1991	CFP mailed. Letters of Intent due 1 April 1991
April 1991	CFP Attachments mailed to those whose letters of intent were received
May 1991	Proposals due
June 1991	Proposals evaluated and accepted in Columbus, Ohio
August 1991	Planning Committee reorganized and renamed as *IGS Campaign Oversight Committee* at the 20^{th} IUGG General Assembly in Vienna
October 1991	First IGS Campaign Oversight Committee Meeting in Greenbelt

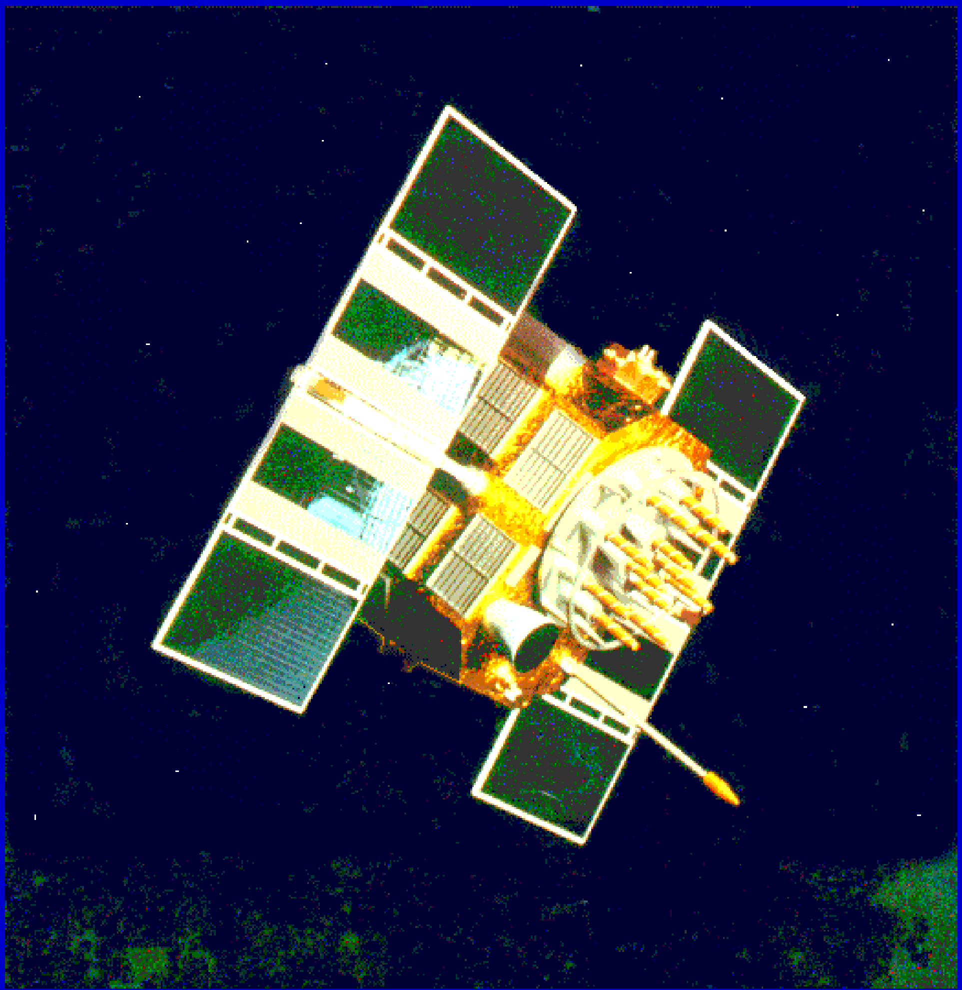
- In the 1980s software packages capable of orbit improvement were available and the CIGNET (Cooperative International GPS Network) existed.

The GPS in 1992 and in 2004



- On June 21, 1992, there were 17 active GPS satellites, 4 of them still Block 1.
- In 2004 there are 27 active GPS satellites, 3 of them still Block 2.
- The satellites are in six orbital planes, separated by 60^{o} in the equator, inclined by 55^{o} to it.
- Rev.per.=1/2 sid. day.

The GPS-Satellites

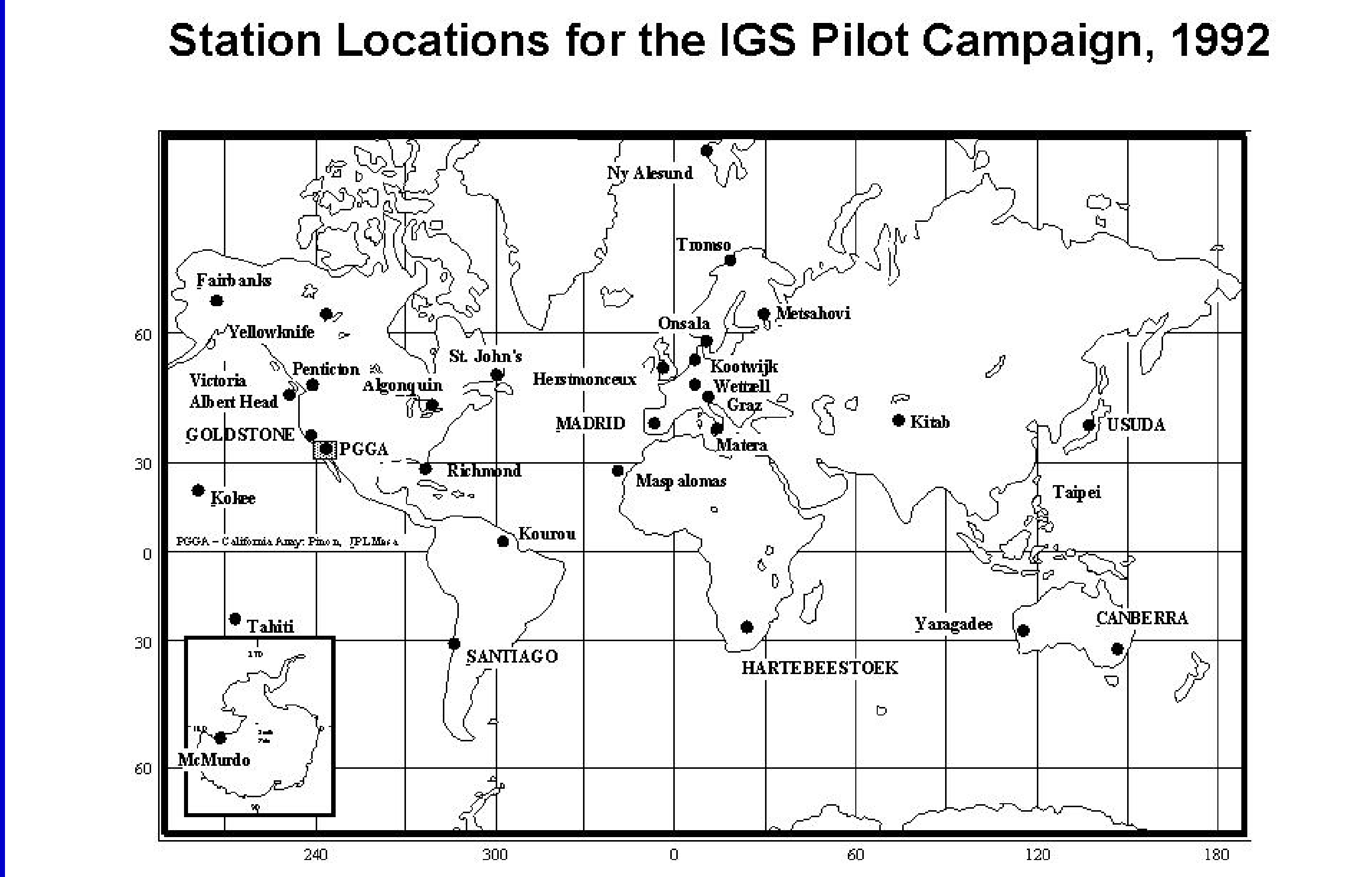


- GPS-Satellites transmit coherent signals on two carriers.
- The carrier wavelengths are λ_1=19cm, λ_2=24cm
- The satellite types are evolving from Block I to II to IIa, IIr, and IIf.
- Weight about 1000 kg, size about 4x4x2 m.

IGS Proof of Concept Phase

- Principal IGS Components
  - Network of tracking sites
  - Global (CDDIS,SIO,IGN), regional, and operational data centers
  - Analysis Centers (CODE, EMR, ESA, GFZ, JPL, SIO, UTX)
  - Analysis Coordinator (Clyde Goad)
  - Central Bureau (Director Ruth Neilan)
  - Campaign Oversight Committee (later on named IGS Governing Board)

Global IGS Tracking Network in 1992



- About 20 useable receivers (mainly ROGUE).

Proof of Concept Phase

Date	Event
March 1992	2nd IGS OSC Meeting at OSU, Columbus, Ohio
May 1992	Communication test
May 1992	Establishment of IGS Mailbox at University of Bern
June 21, 1992	Start of IGS Test Campaign 1992
July 1992	First results!
July 27, 1992	Start of Epoch'92 campaign, lasting for two weeks
September 23, 1992	Official end of the campaign, continuation on best effort basis
November 1992	Start of IGS Pilot Service
March 1993	1st IGS Workshop in Bern, IGS Terms of Reference drafted
May 1993	Meeting of the OSC in Baltimore
August 1993	IAG Approval for IGS at IAG Scientific Meeting in Beijing
October 1993	IGS Analysis Center Workshop
October 1993	IGS Network Operations Workshop and First Governing Board Meeting
December 1993	2nd Governing Board Meeting in San Francisco

- Since June 21, 1992, uninterrupted series of orbits and other products available through the IGS (initially not yet combined products).

Proof of Concept Phase

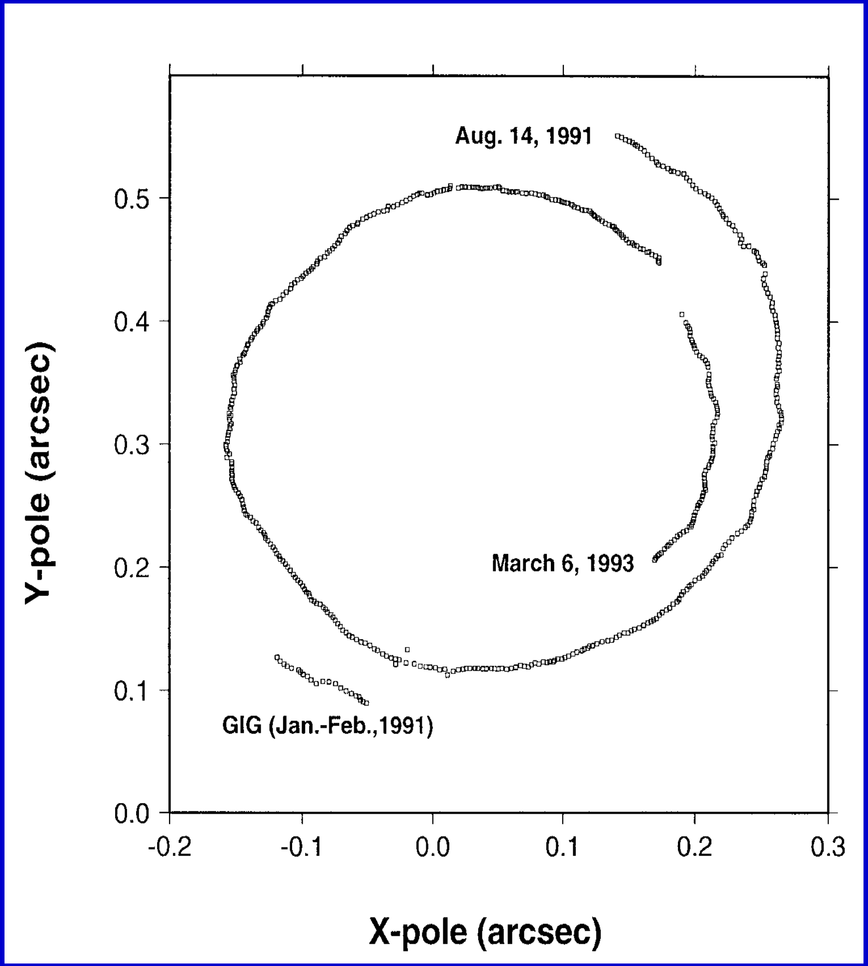
	COD	SIO	JPL	EMR	ESA
COD	--	43	46	38	87
SIO		--	48	39	81
JPL			--	33	75
EMR					70

- Mean rms of 7-parameter Helmert trafo between pairs of solutions (Nov 92-Nov 93) (taken from ACC Report in Bern 1993 proc.).

- Orbit accuracy of best solutions around 30cm.

- This was more than a factor of 10 better than the broadcast orbits!

Proof of Concept Phase



- Typical result (SIO) for polar motion. Accuracy about 1 mas per coordinate for daily estimates (from Bern Proceedings, 1993).
- It became clear that ERPs had to be estimated and could not be taken over from other sources (IERS).

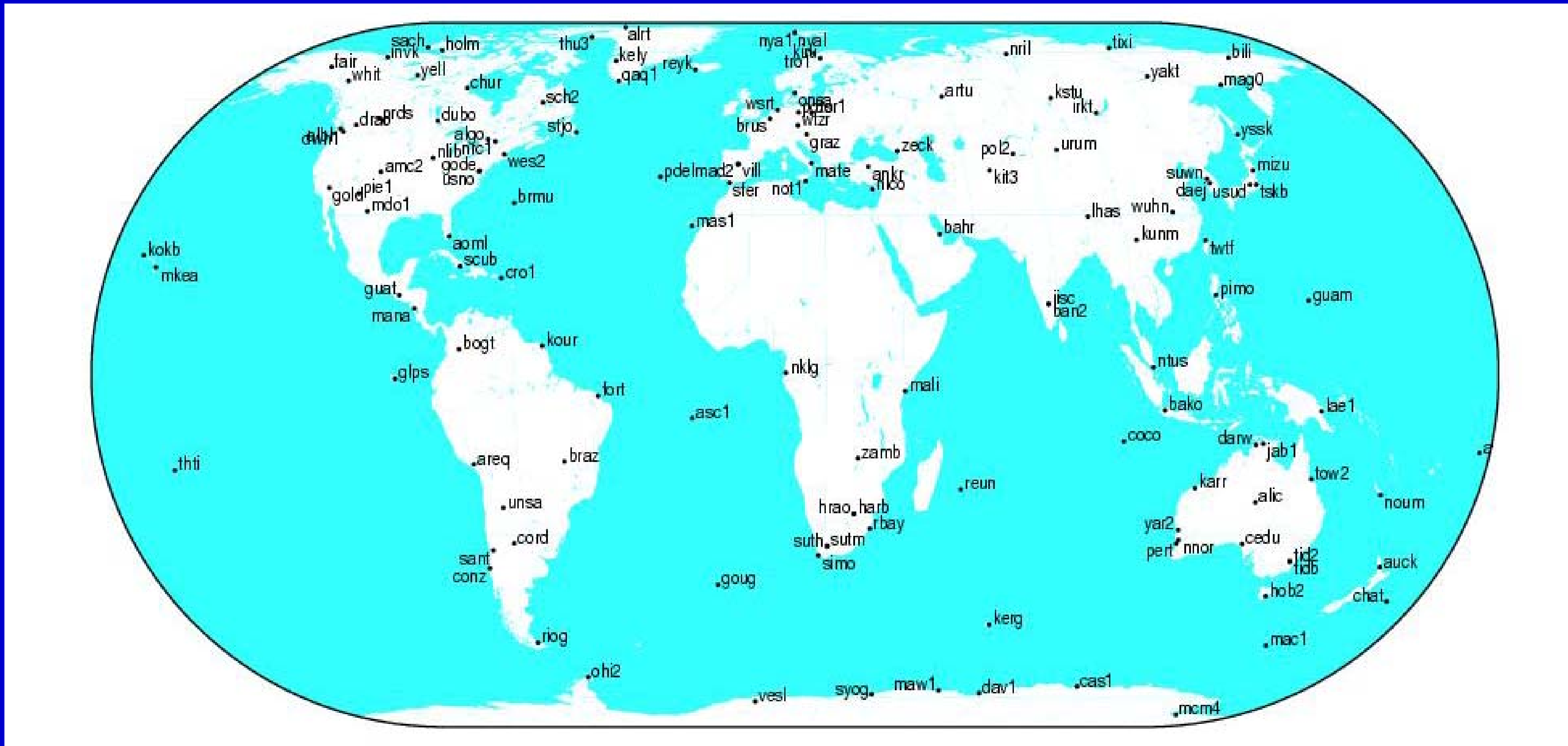
The IGS as an Official Service

- The IGS made *tremendous progress* in the following domains:
  - *altius, citius, fortius:* the observational basis was improved, the delay between the availability of data and products was reduced, the analysis was substantially improved and made more robust.
  - The GPS *signal is noe fully exploited*, leading to new and attractive applications.
  - The service was *generalized* to “not only” include GPS, but also *GLONASS* satellites.
  - Applications to LEOs carrying spaceborne receivers are studied.

The IGS as an Official Service
altius, citius, fortius

- The number of sites of the IGS grew dramatically.
- The adherence to standards by the IGS ACs was considerably improved.
- Analysis tools became more and more mature.
- Modeling was generalized to include LoD, drifts of polar motion, better resolution, etc.
- Delays in data transmission reduced.
- Rapid and ultra-rapid products could be generated.
- All products were systematically compared & combined.

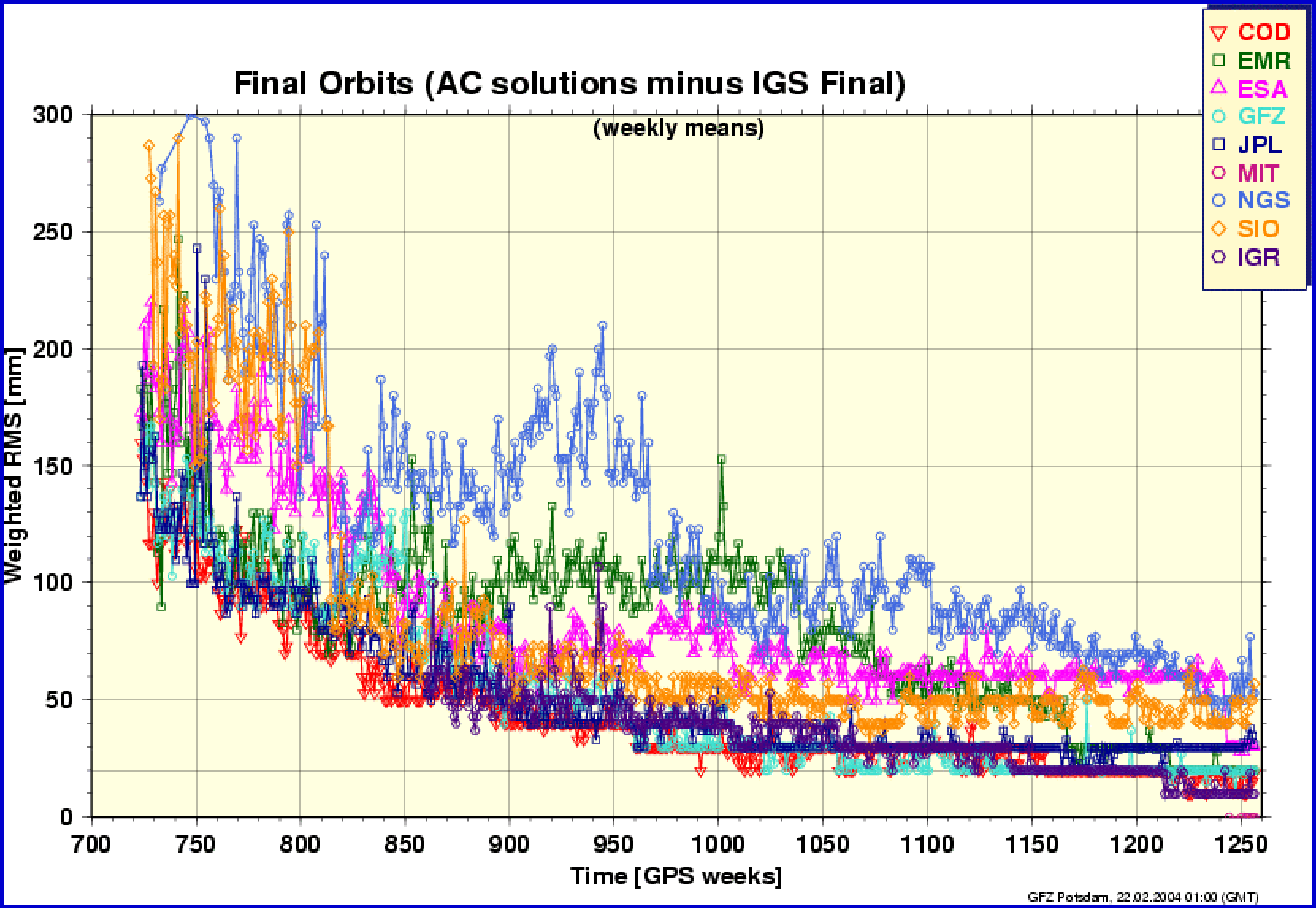
The IGS as an Official Service



• The IGS Global Network grew from 20-30 in 1993 to well over 300 sites in 2004.

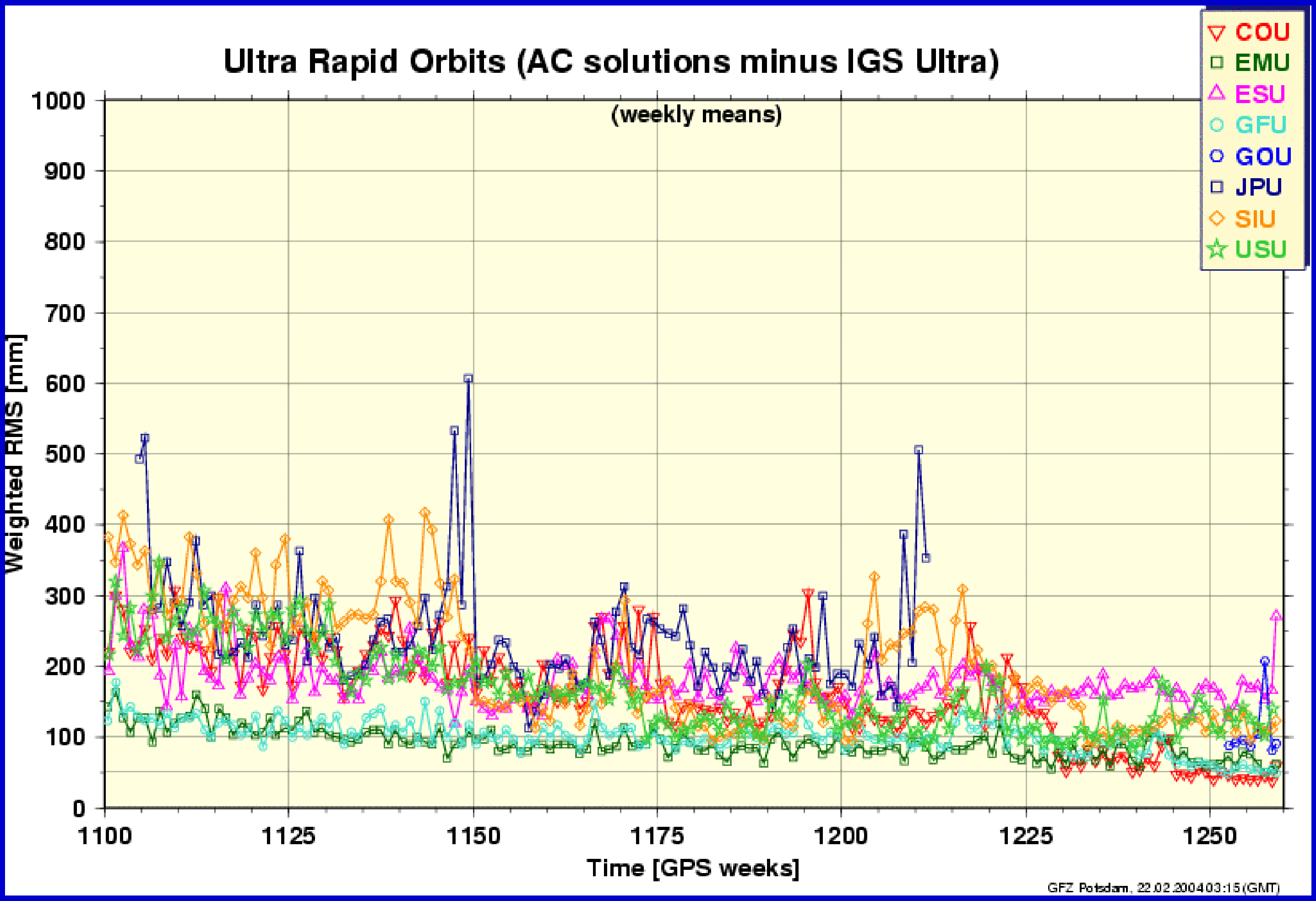
•Adherence to standards is not trivial!

The IGS as an Official Service



•Orbit quality improved from 20cm in 1993 to 2-3 cm in 2004 (from ACC homepage).

The IGS as an Official Service



- Ultra rapid orbits (available in real-time) since February 2001. Accuracy today < 10cm.

The IGS as an Official Service

Date	Event
January 1994	Start of official service on January 1
November 1994	Workshop on the *Densification of the ITRF* at JPL, Pasadena
May 1995	IGS Workshop on *Special Topics and New Directions* at GFZ in Potsdam
March 1996	IGS Analysis Center Workshop in Silver Spring, USA
March 1997	IGS Analysis Center Workshop at JPL in Pasadena
December 1997	IGS Retreat in San Francisco
February 1998	IGS Analysis Center Workshop at ESOC in Darmstadt
December 1998	Prof. Christopher Reigber elected as IGS Chairman 1999-2002
March 1999	LEO Workshop, Potsdam, Germany
June 1999	Analysis Center Workshop, La Jolla, California
March 2000	IGS Tutorials in South Africa
May 2, 2000	Selective Availablitiy removed!!
July 2000	IGS Network Workshop
July 15, 2000	CHAMP Launch
September 2000	IGS Analysis Center Workshop at USNO
December 2000	IGS Strategic Planning Meeting
February 2001	LEO Workshop
March 2001	Glonass Service Pilot Project
M;arch 2001	TIGA Project established
April 2002	Ottawa Workshop: Towards Real-time
July 2002	UN Regional GNSS Workshop
December 2002	Prof. John Dow elected as IGS Chairman 2003-2006
April 2003	Ionosphere maps (IONEX) etc. official IGS product
May 2003	First operational combined GPS/GLONASS analysis products
August 2003	Essential improvement of “near-real-time” orbits
March 2004	IGS Analysis Center Workshop and 10 Years Symposium

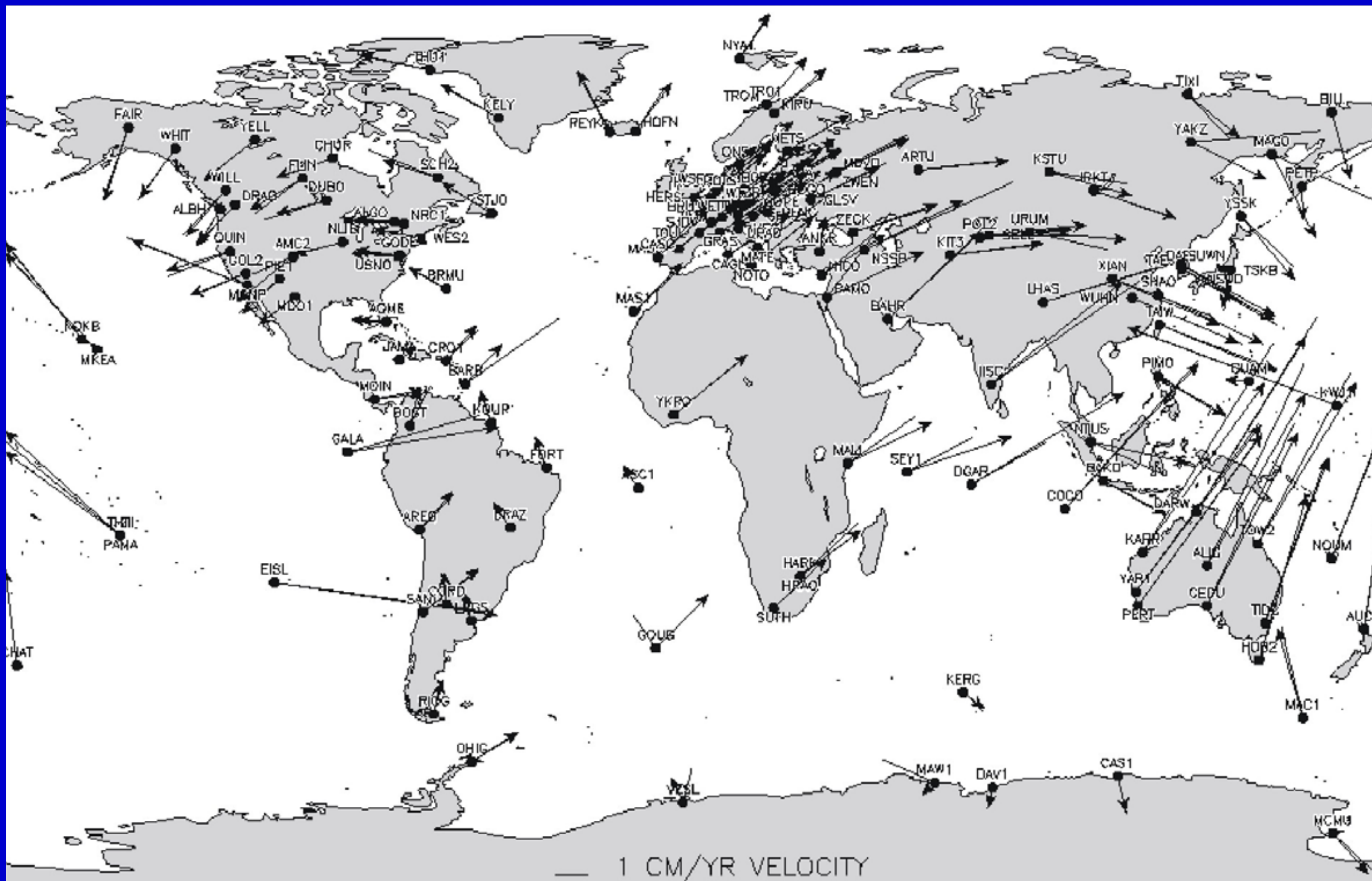
The IGS as an Official Service
Full exploitation of signal

- The (unambiguous) GPS observation equation:
- $c\,(t_r - t^s) = \rho + c\,(\Delta t_r - \Delta t^s) + \Delta\rho_i + \Delta\rho_t$
- The distance ρ is used to determine receiver position, the orbit of the satellite, and ERPs.
- $c\,(\Delta t_r - \Delta t^s)$ is used to synchronize clocks,
- $\Delta\rho_i$, the ionospheric signal delay, is used to derive ionosphere maps, and
- $\Delta\rho_t$, the tropospheric signal delay, is used for GPS meteorology.

The IGS as an Official Service
Full exploitation of signal

- Exploitation of ρ : Orbits, station coordinates (and velocities) are *core products* of the IGS since 1992.
- Exploitation of Δt_r - Δt^s : In 1997 the *IGS/BIPM Project to Study Accurate Time and Frequency Comparisons* was created. The **IGS time scale** was developed in the framework of this project.
- Exploitation of $\Delta\rho_i$: The IGS ionosphere working group, created 1998, defines, compares and combines ionosphere products.
- Exploitation of $\Delta\rho_t$: The troposphere combination center was established at GFZ in 1997, a troposphere working group was created.

Monitoring Plate Motion

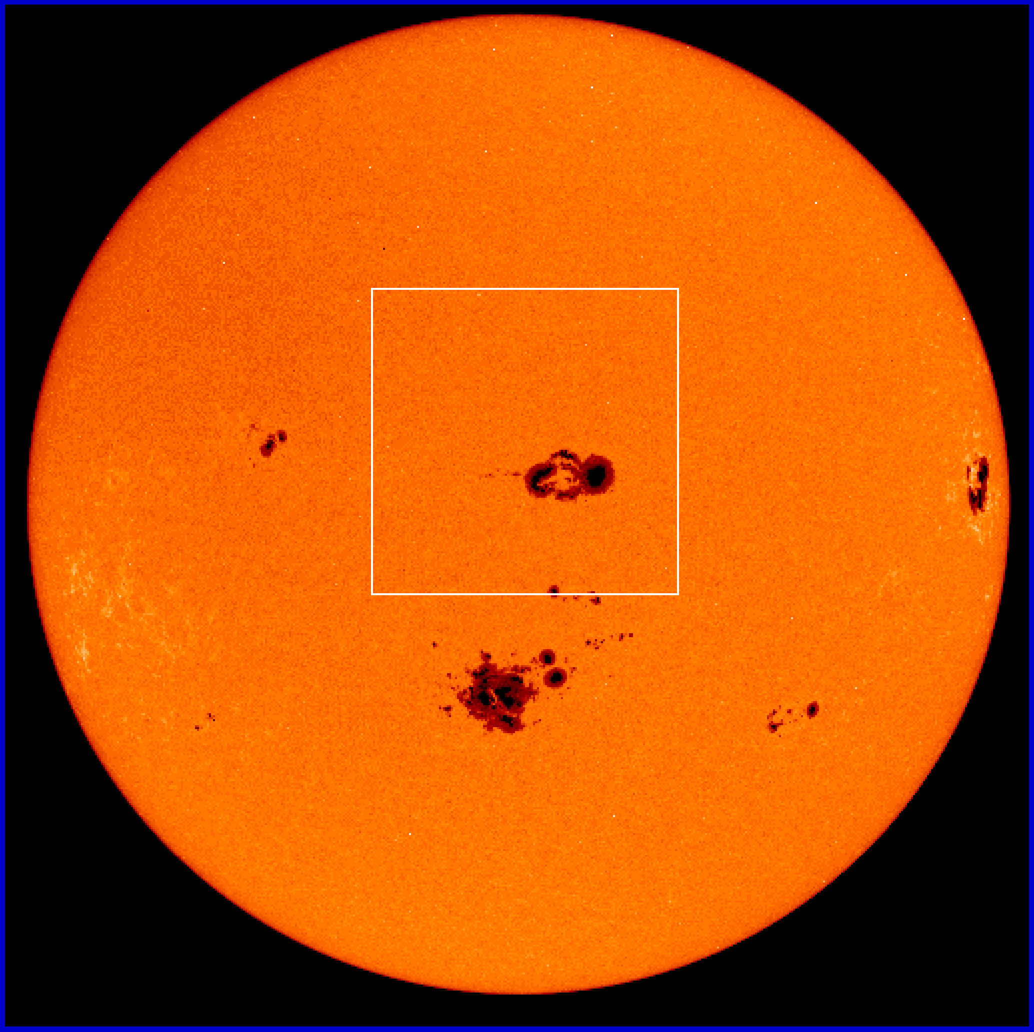


• The IGS monitors *plate tectonics* in "real time". Density of stations and time resolution of station motion are unprecedented.

Northern Lights

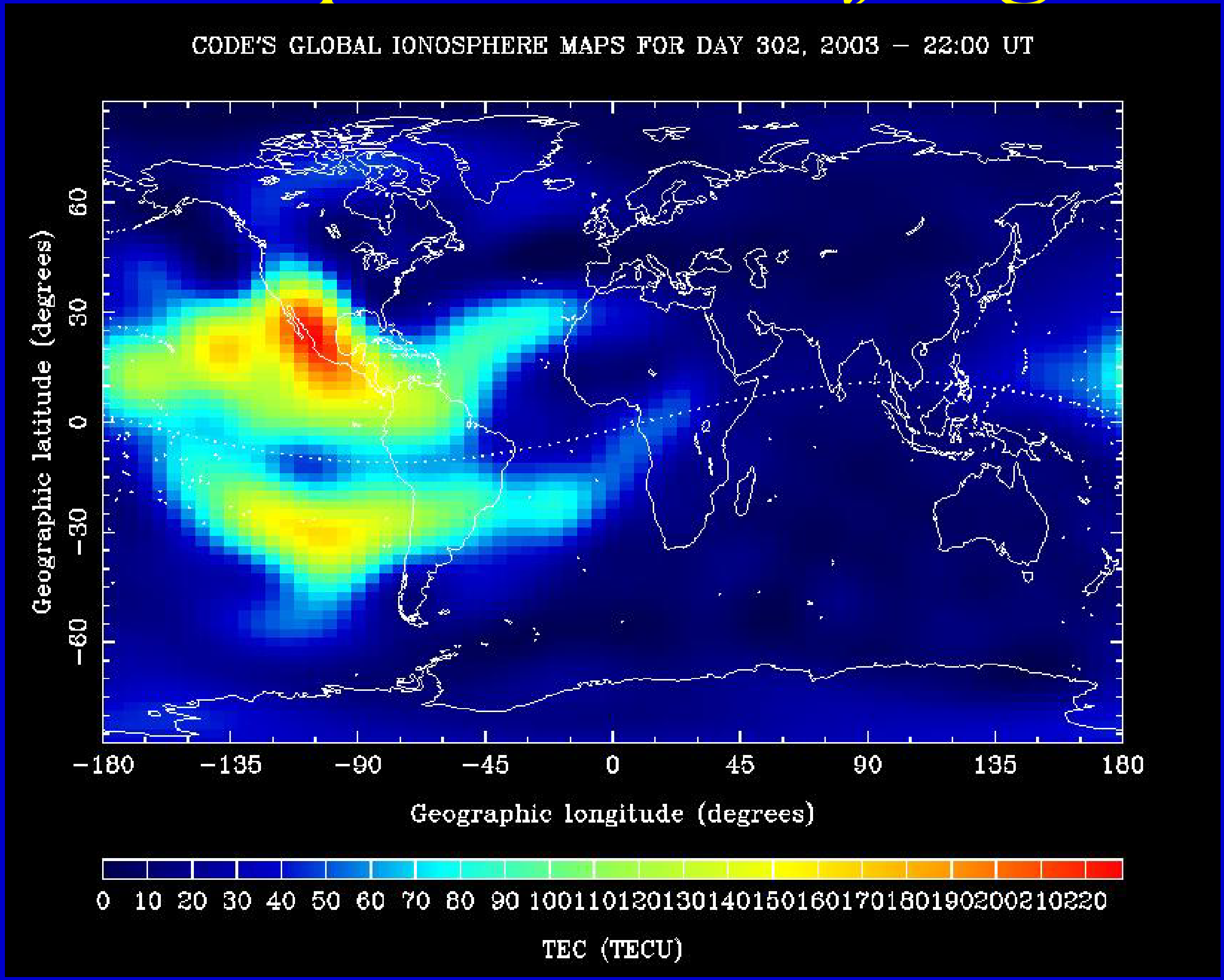
- Northern lights in Basel (Metzerlen) on Nov 20, 2003, about 21^h, Photo: R. Nufer

Solar Activity in Fall 2003



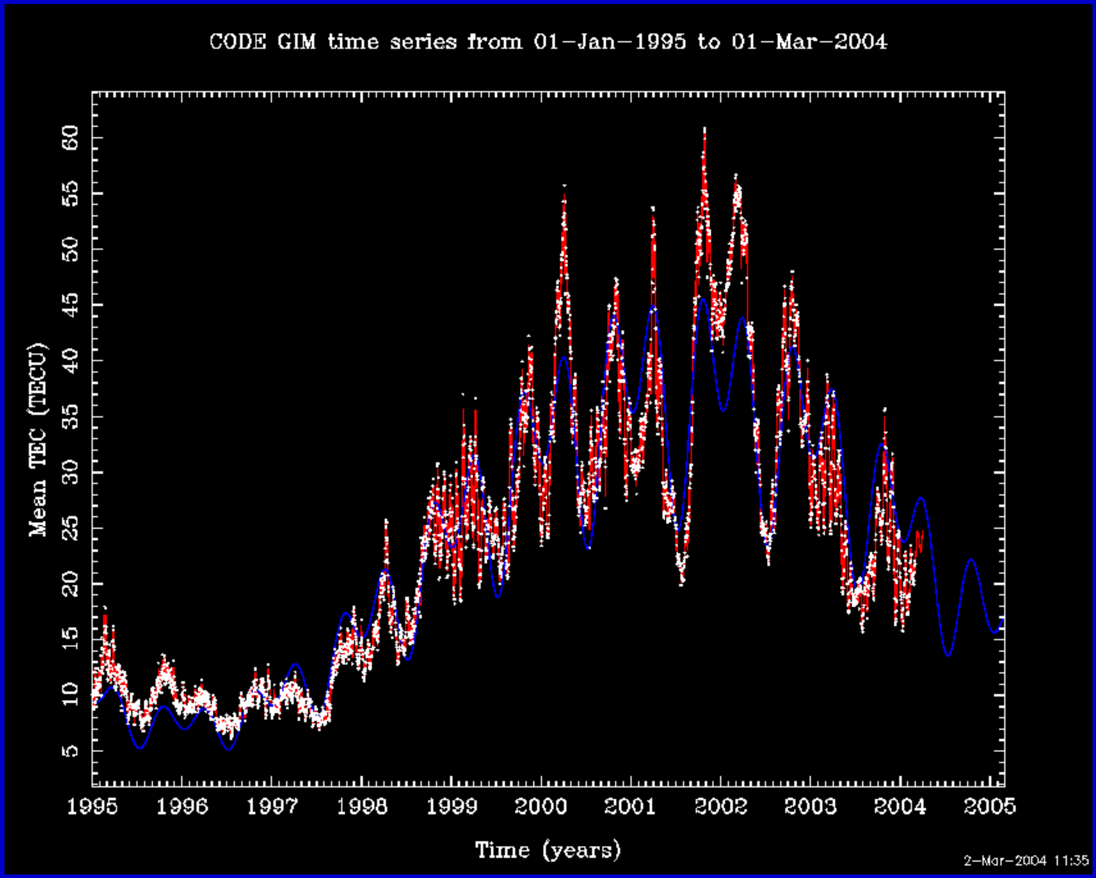
- The Sun, as observed by SOHO on October 29, 2003.

The IGS as an Official Service
Full exploitation of signal



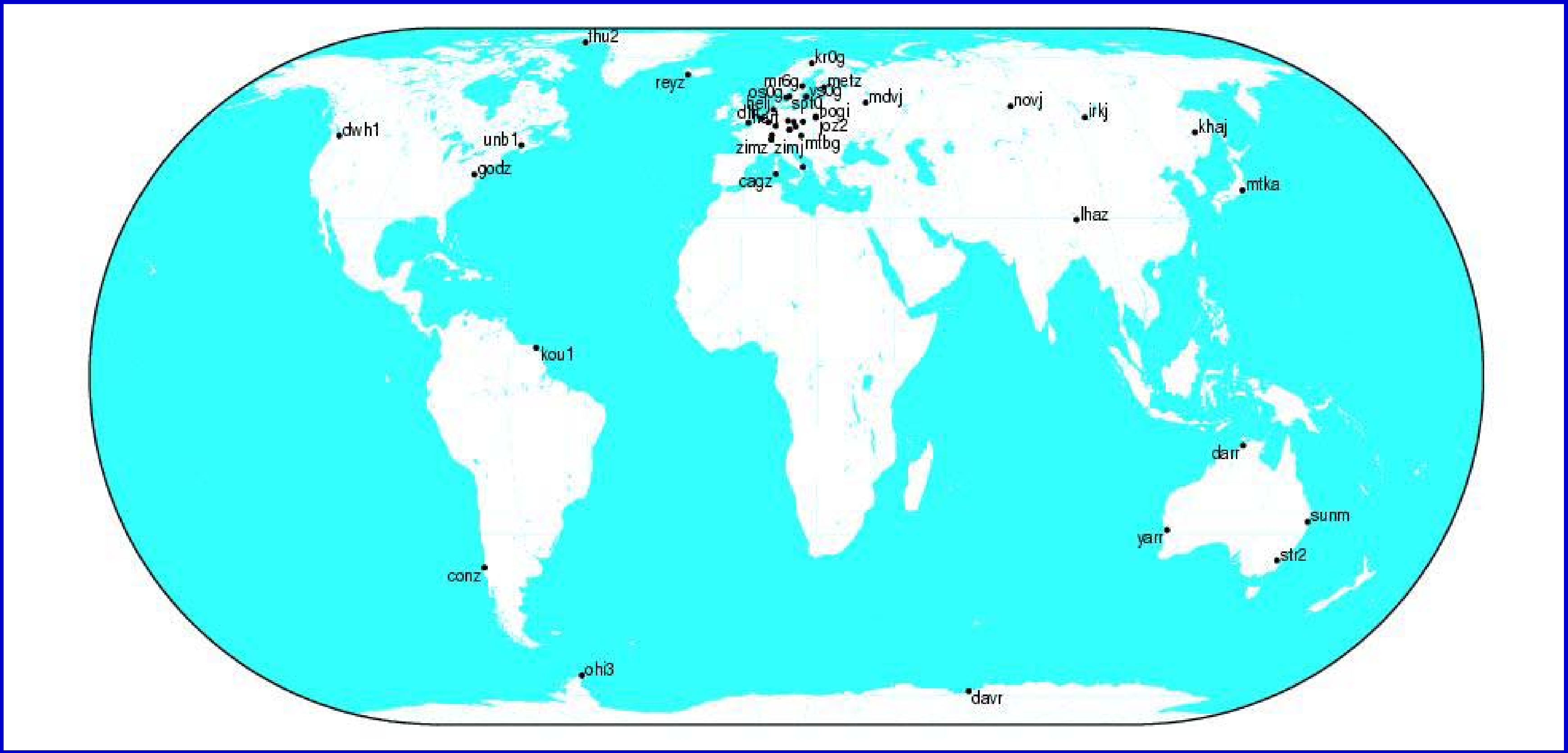
- Exceptionally high TEC values observed by IGS on October 29, 2003

The IGS as an Official Service
Full exploitation of signal



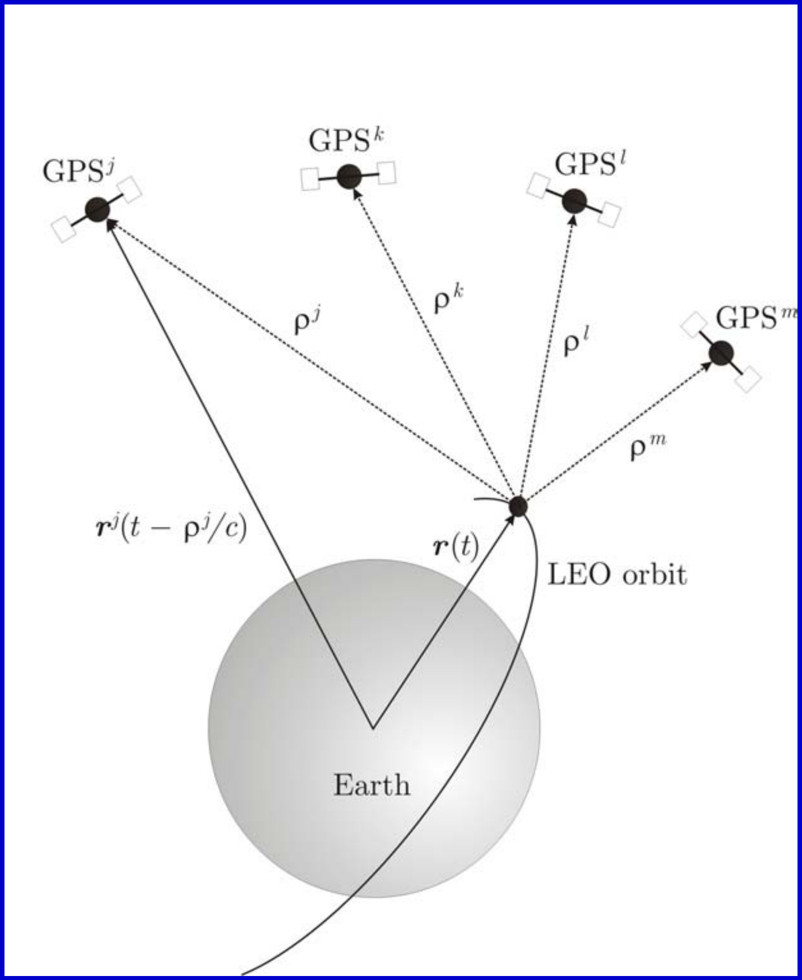
- Mean TEC was high, but not extraordinary on Oct 29, 2003.

The IGS/GLONASS Network



- About 20 IGS stations are equipped with GPS/GLONASS receivers
- IGEX-98 Campaign in 1998/99, IGLOS-PP since 2001, 10-cm GLONASS orbits available in regular IGS products since May 2003.

Use of Spaceborne GPS Receivers



- Using the IGS products (GPS orbits, clocks, ERPs) kinematic trajecories of LEOs of cm-acuracy can be established with precise point positioning.
- One would have to invent the IGS for this purpose!
- Most LEOs will be equipped with spaceborne GPS receivers in future.

Use of Spaceborne GPS Receivers

- CHAMP, launched in summer 2000, explores gravity field (+magnetic field and atmosphere) using spaceborne GPS receiver.

•IGS observations and/or products *needed* for POD (cm-accuracy).

Key Elements of IGS Success

- The IGS is based on *user demands* and *needs*.
- *Redundancy* in network, data centers, analysis.
- IGS generates combined products ==> *robustness*.
- IGS is fully (understanding and) exploiting the GPS signal ==> *Interdisciplinarity*.
- Friendly competition of analysis centers ==> *Stimulating research & development environment*.
- IGS is developing into a GNSS service ==> *Authority for scientific exploitation of GNSS*.

IGS Impact on new IAG Structure

- IGS and IERS are to a large extent responsible for the positive image of geodesy in 1990.
- The role of the services is reflected in the 2003-2007 IAG structure:
  - Services are elements of IAG on the same level as the Commissions.
  - 3 representatives of services (Neilan, Rothacher, Schuh) are members of IAG Executive Committee.
  - Interfaces between services and commissions are being set up.

IGS Impact on new IAG Structure

- The success of the services stimulated the attempt to create the IAG project ***IGGOS***:
  - *IGGOS* stands for *Integrated Global Geodetic Observing System*.
  - *IGGOS* is based on IAG services.
  - *IGGOS* should be recognized by the “outside world” as geodesy’s contribution to Earth sciences.
  - *IGGOS* strives for consistency on 10^{-9}-level of geometry, gravity, and ERP.
  - *IGGOS* strives for preservation of global geodetic infrastructure and its use for monitoring the Earth.

Impact of the IGS on the Future of Geodesy

- The impact can hardly be overestimated:
  - The current GNSS systems (GPS, GLONASS, Galileo) will be dominating tools for positioning and navigation (at least) in the next two decades.
  - The IGS provides the foundations for the scientific exploitation of these system in a *very broad sense.*
  - The accurate terrestrial reference system(s), monitoring of Earth rotation, gravity field determination, exploration of important aspects of the atmosphere will be based to a large extent on these systems.

Challenges of the IGS in the Future

- The IGS will have to play a proactive role in the framework of IGGOS. There must be a proper balance with the other space-geodetic techniques.
- The research opportunities, which may be derived from the IGS and its products are almost unlimit-ed. To exploit them, we need interfaces with
  - IAG commissions, IGGOS project
  - other Earth science communities.
- The IGS will be one of the most vital elements in geodesy, provided its work will be pursued in the same spirit as in the previous ten years.