THE INTERNATIONAL GPS NETWORK FOR CHART] N(; THE EVOLVING GLOBAL REFERENCE FRAME

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ABSTRACT

The Telecommunications and Engineering Division of Caltech's Jet Propulsion Laboratory is funded by the National Aeronautics and Space Administration (NASA) to play a variety of roles in applying the Global Positioning System (GPS) to geodesy and geodynamics. Among these arc (i) the operation of dozens of globally-distributed, permanently-operating 1 Earth-fixed GPS stations; the collection, archiving, and distribution of data from this network, as well as from GPS stations operated by other domestic and foreign agencies; (ii) the regular analysis of data from the global GPS network, which result in few-nliliimctcl-level estimates of site coordinates and sub-decimeter estimates of GPS satellite ephemerides; and (iii) the coordination of international GPS activities that relate to geodynamics, by serving as the Central Bureau of the

INTRODUCTION

those fixed parameters worsens as the contour levels increase. Continued expansion of the global network will reduce the extent of these isolation contours.

In this paper, we discuss the efforts by NASA and the international scientific community to produce highly accurate GPS products to benefit a broad user community. The GPS activities at JPL are presented, the International GPS Service for Geodynamics (IGS) is described,

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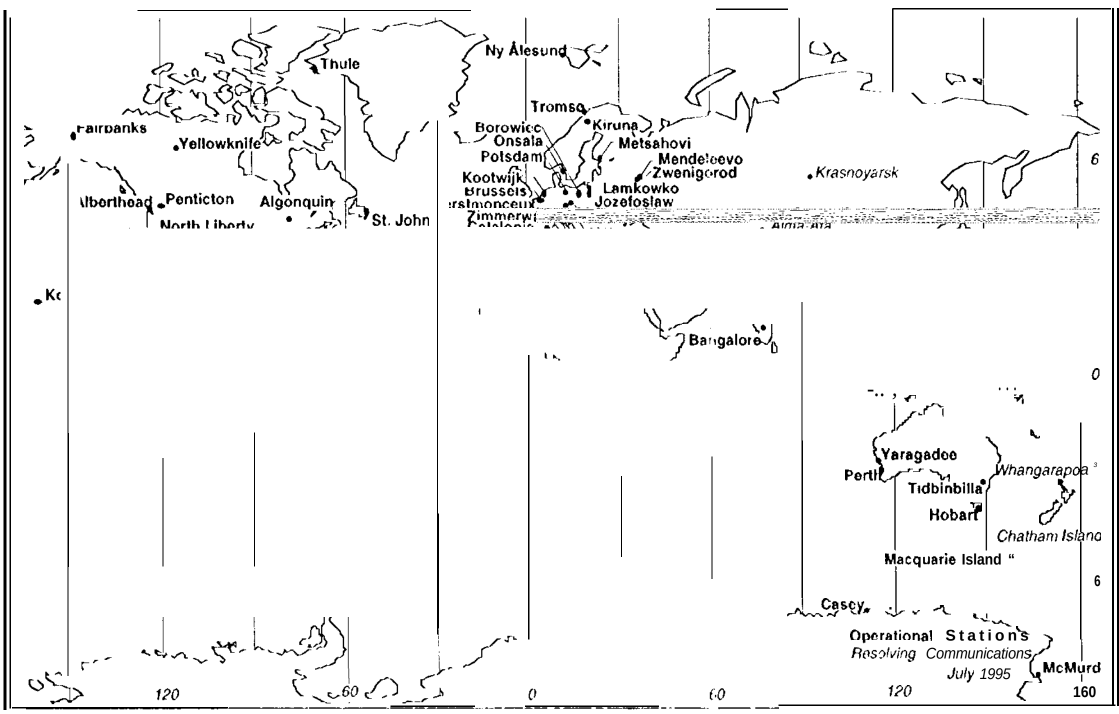

Figure 1. Continuously operating permanent sites in the GPS global network, July 1995.

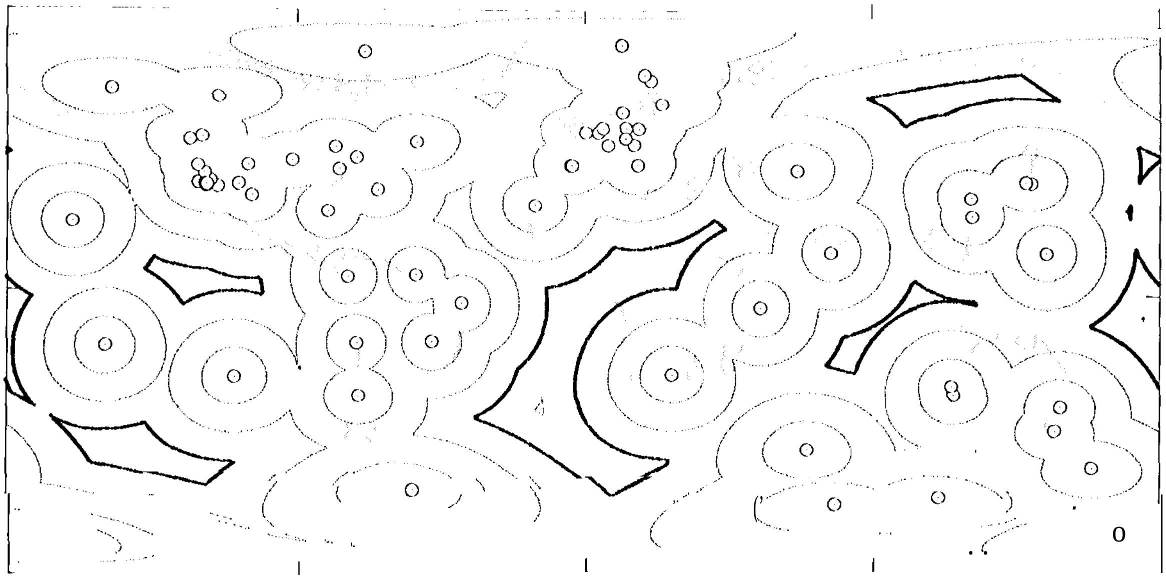

Figure 2. Isolation contour map of the GPS global network, July 1995. The contour interval is 1000 km, with the 3000-km contour in bold. Only a handful of regions exist that arc further than 3000 km from a permanent silt, and planned expansion will cl iminate nearl y al 1 of these before 2000.

formatted GPS data directl y from GPS receivers and also raw and formatted data from several network partners. The formatted GPS data arc currently made available on-line for 120 days and archived both on site and off site on CD-ROM discs after 40 days. The archiving of data is performed once pcr week, when 3 CD-ROM disc copies arc made of the GPS data (one stored off-site). The format ted data arc stored in the R] NEX format and compressed using t hc standard

Data Access

The data may be accessed via anonymous FTP from bodhi.jpl.nasa.gov (128.149.70.66) under /pub/rinex. The data are listed by day-of-year, and the file naming convention is the GIPSY software convention (ddmmmyyname______r0.rnx_z). The '_z' indicates the UNIX compression of the file. Tables 1 and 2 below summarize the access paths. Descriptions of actual installations of GPS monuments and receivers installed by JPL for the Los Angeles basin GPS densification project can be found on the W W W at:

http://milhouse.jpl.nasa.gov/

Table 1. Data Access Information

Short Name:
institution:
Function within IGS:
Mail Address:

Contact:
Telephone:
Fax:
E-Mail:
FTP Access:
Computer Operating

most directly involved and have analyzed data from a globally-distributed network of GPS receivers beginning with the first Global International GPS experim ent in 1991 [1].

Our analysis strategy consists of using the ionosphere-free combination of both pseudorange and carrier phase, with data noise values of 1 cm and 1 m, respectively. Data below 15 degrees elevation are excluded. The phase data are decimated to 5 mi nut es, and the pseudorange data are carrier-smoothed over the same interval.

Data corresponding to each GPS day are analyzed in 30-hour batches centered on GPS noon. Estimated parameters were satellite state vectors and solar radiation pressure (srp), receiver coordinates, zenith wet troposphere delay at each receiver site, station and satellite clock offsets, carrier phase ambiguities, and Earth orientation. Satellite x- and y- srp and y-bias parameters are allowed to vary stochastic all y. Zenith wet troposphere delay is modeled as a random walk with 1 cm^2/hr variance derivative, and is itself further anal yzed for cl imatological applications.

Solid Earth and ocean tides are modeled largely in accordance with the IERS standards [2], [3]. The Earth's gravity field is described by the JGM-3 12x12 multipole expansion using terms up through degree anti order 12 [4]. The value of GM used was 39860(].4415 km^3/s^2 [5]. Note that because of the use of the recent value of GM, the orbital ephemerides described below require a scale transformation in addition to rigid rotations to be expressed in the WGS-84 frame. Nominal values of the parameters for each GPS satellite. [3 each for position and velocity, anti two for srp are from the broadcast ephemeris. Weak *a priori* constraints of 1 km and 10 mm/s for position and velocity, respectivel y, are imposed. The '1' 10-T20 solar radiation pressure model is used for srp [6], while the new yaw at t itude model [7] is applied for ecl ipsing spacecr aft.

As an example, the analysis of January 21, 1994 included data from 43 stations and 25 satellites. There were nearly 60,000 phase and pseudorange measurements each, from which 1556 parameters were determined. (]'ammeters allowed to vary stochastically are counted only once. These include station and satellite clocks, station zenith wet troposphere delay, and satellite srp). The rms post-fit residuals for the phase measurements were t ypical 1 y a few mm. Those measurements with more than S-cm post-fit residual for phase, or 5 m for pseudorange, were considered outliers and excluded.

Results

Results for station coordinates and Earth orient at ion, independent of errors in fiducial coordinates, are described in [8]. Typical daily repeatabilities of site coordinates are. 3, 5, and 9 mm in the north, east, and vert ical components, respectivel y, with respect to a global reference frame with origin at the Earth's mass center. Baselines between nearby sites can be significantly better due to cancellation of common orbit, clock, and media errors. The performance of the operational Earth orientat ion series with respect to the IERS Bulletin B Final values is at the 0.3 -milliarcsecond level, which is equivalent to about 10 mm on the Earth's surface.

Our single most important measure of orbit quality is the extent to which estimated values of a satellite's position near midnight agree with similar estimates based on data from adjacent days. For a given satellite and day we define tile orbit repeatability Q to be the rms, during the 6 hours around midnight and over al 1 3 orbi t posit ion components, of the di fferences bet ween t he orbit computed using the. current day's data and that computed with the previous (or next) day's data. Since there is onl y one "(rue" orbit during this period, the differences ar e a good measure of orbit accuracy, The value of Q is typically 1 O -20 cm (3-dimensional rms) during 1994-9S. This is at least one order of magnitude better than the GPS broadcast orbits, which are in the few-meter range. The precise orbits, and the GPS spacecraft clock offsets which are. con sistent with them, are routine] y computed and made available to the public as described below. Our nominal goal is to deliver a week's worth of products on Friday (or earlier) following the Saturday that marked the close of the previous GPS week.

Precise Point Positioning

in late 1994, **in response to** the growing number of regionally dense GPS sites (for example in California and Japan), wc adopted a strategy of using an

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pub/gipsy_products/1995/clocks/1995-04-01 badCLOCK.Z
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pub/gipsy_products/1995/orbits/1995-04-01.eci.Z
pub/gipsy_products/1995/orbits/1995-04-01 tpeo.nml.Z

contain information on respectively, precise GPS clock solutions, times and satellites for which precise clock solutions are unavailable, information on the attitudes of eclipsing GPS spacecraft, precise satellite ephemerides in an Earth-centered inertial reference frame, and Earth orientation information. More information can be obtained from gipsy@cobra.jpl.nasa.gov.

Finally, WWW pages located at

http://sideshow.jpl.nasa.gov/mbh/series.html

and

http://sideshow.jpl.nasa.gov/mbh/point.html

provide graphical time series of station coordinates.

Improving Turnaround and Automation

Beginning in April 1995, an automated process developed by the EOS Group provides rapid precise orbits and clocks, within about a day of the end of data collection. These orbits are accurate to a few tens of cm, and very valuable in their timeliness.

A second automated process periodically looks for new data files from IGS sites. If satellite parameters from the rapid orbit service are available for the corresponding day, such data are analyzed with precise point positioning. Both engineering data and site coordinates are saved. This process runs asynchronously with the rapid orbit service. This automated processes is being used for before-the-fact quality control procedures in the normal AC operation.

Finally, we intend to provide values of the GPS spacecraft clocks at finer temporal resolution than the current 5 minutes. Providing solutions at 10-second resolution should allow use of the JPL orbits and clocks for point positioning in kinematic post-processing applications, including ground and aircraft positioning at the centimeter level, since interpolation of the 10-second values should be relatively insensitive to the clock dithering of Selective Availability (SA).

THE INTERNATIONAL GPS SERVICE FOR GEODYNAMICS

The international GPS Service for Geodynamics is an international scientific service which began formal operation at the beginning of 1994, following several years of planning and a 1 ½-year pilot service. The primary objective of the IGS is to provide a service to support, through GPS data products, geodetic and geophysical research activities. Cognizant of the immense growth in GPS applications the secondary objective of the IGS is to support a broad spectrum of operational activities performed by governmental or selected commercial organizations. The service also develops the necessary standards/specifications and encourages international adherence to its conventions.

To accomplish its mission, the IGS consists of a network of GPS tracking stations, Data Centers, Analysis Centers, an Analysis Coordinator, a Central Bureau, and a Governing Board. The accuracies of IGS products are sufficient to support current scientific objectives, including the realization of the international Terrestrial Reference Frame (ITRF), monitoring of the Earth's rotation and deformation of its liquid and solid components, ionospheric monitoring, and scientific satellite orbit determination. A Central Bureau information System allows public access to IGS products, which include precise GPS ephemerides within 2-3 weeks of real time. IGS contributors and customers communicate through electronic mail, and exchanges arc archived for future reference.

A proof of concept for the international GPS Service. for Geodynamics was conducted with a three-month campaign during June- September 1992, and was continued through a pilot service until the formal establishment of the IGS in 1993 by the International Association of Geodesy (IAG). The routine IGS started on January 1, 1994. IGS operates in close cooperation with the international Earth Rotation Service (IERS). The IGS *Terms of Reference* describes in broad terms the goals and organization of the IGS [11]. The IGS collects, archives, and distributes GPS observation data sets of sufficient accuracy to satisfy the objectives of a wide range of applications and experimentation. These data sets arc used by the IGS to generate data products, including high accuracy GPS satellite ephemerides, Earth rotat ion parameters, coordinates and velocities of the IGS tracking stations, GPS satellite and tracking station clock information, and ionospheric information. in particular the accuracies of these products arc sufficient for the improvement and extension of the International Terrestrial Reference Frame (ITRF), the monitoring of solid Earth deformat ions, the monitoring of Earth rotation and variations in the liquid Earth (sea level, icc-sheets, etc.), for scientific satellite orbit determinations, and ionosphere monitoring.

Operation of the IGS

Each site. has a high-precision dual-frequency P-code receiver which records measurements at 30-sec intervals. IGS operational Data Centers (Table 3) arc in direct contact with the tracking sites, and arc responsible for fetching raw receiver data, formatting it in a common standard [12], and forwarding the data to Regional or Global Dat a Centers Reformatted tracking data from several Operational Data Centers arc collected at Regional Data Centers. A local archive of the data received is maintained, and the data arc transmitted to the Global Data Centers. Regional Data Centers thus serve to reduce traffic on electronic networks,

Table 3. IGS Data Centers

Operational & Regional	
National Oceanic and Atmospheric Administration	US
Institut für Angewandte Geodäsie	Germany
Natural Resources, Canada	Canada
Norwegian Mapping Authority	Norway
Jet Propulsion Laboratory	US
Australian Land information Group	Australia
Global	
NASA/Goddard Space Flight Center	US
Institut Géographique National	France
Scripps institution of Oceanography	US

The Global Data Centers serve as interfaces to the Analysis Centers and the external user community. Their purpose is to receive/retrieve, archive, and provide on-line access to tracking data. In addition, Global Data Centers provide access to Analysis Center products.

There arc currently seven **IGS** Analysis Centers (AC's) (Table 4) - three in the US, one in Canada, three in Europe – that routinely analyze some subset of the data from the IGS global net work. AC'S compute precise GPS ephemerides and Earth orientat ion parameters. Daily results are posted periodically, typically once each week.

The IGS Analysis Coordinator is responsible for producing a single IGS orbit, based on the combination of orbits from the separate AC's [13]. Because of consistency checks, the combined orbit is largely free of some systematic errors that occasionally remain in results from individual AC's. Agreement among AC's in GPS satellite ephemerides is generall y at the level of 10 to 30 cm.

It is estimated that the absolute accuracy of the IGS orbits is at least one order of magnitude better than the broadcast ephemeris, even when anti-spoofing is in effect,

"1'able 4. IGS Analysis Centers

Astronomical Institute-University of Berne	Switzerland
European Space Agency	Germany
GeoForschungsZentrum	Germany
Jet propulsion Laboratory	US
National Oceanic and Atmospheric Administration	11s
Natural Resources, Canada	Canada
Scripps Institution of Oceanography	US

Estimates of 1 earth orientation and station coordinates from the AC'S are coordinated with the IERS. Through the IGS, GPS-derived station locat ions arc contributing more and more to the ITRF. Over the next few years, a major goal of the IGS will be to include in the ITRF the coordinates of a number of sites that comprise dense regional GPS networks.

Central Bureau Information System

The Central Bureau information System (CBIS) provides public access to products of the IGS, and also provides a means of electronic messaging among IGS participants. The system, developed in late 1993, runs automatically. The CBIS is a client on the Internet's World Wide Web, allowing access with user-friendly Mosaic and 1.ynx interfaces. For example, on most Unix systems, the command

lynx http://igscb.jpl.nasa.gov/

will connect the user to the CBIS. 1 'or those with X-window terminals, xmosaic for Unix systems, or the equivalent Macintosh or Windows application, allows a graphical interface to the CBIS. In the CBIS, one can view **IGS Mail** - an archive of exchanges among IGS participants; **IGS Reports** -- an archive of reports from IGS Data and Analysis Centers; and other IGS-related mail archives. These collections arc also available through **anonymous l"]']'.** Categories in bold (as well as a number of others not listed here) can be selected for further exploration. B y sending a message to igscb @ igscb.jpl.nasa.gov, you can request that your Internet c-mail address be added to one or more of the mail and report distribution lists.

Geodynamics investigators who use GPS in local regions can include data from one or more nearby IGS stations, fix the site coordinates from such stations to their ITRF values, and fix GPS satellite positions to their IGS-determined values. By doing so the investigator can reduce data from his own network with maximum accuracy and minimum computational burden. Furthermore. the results wil be in a well-defined global reference frame. '

CONCLUSION

NASA and J]']. have developed a highly sophisticated GPS network operations and analysis capability. This capability has' resulted in timely and accurate data gathering, archiving, and generation of precise orbits, clocks, and site positions. The use of the JP1. and IGS data centers both for access to raw data and for access to the highly accurate. analysis products can significant] y ease the burden of GPS positioning for a broad range of users. We invite any current or potential user to explore the addresses given above and to cent act t he aut hors for further discussion.

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