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THE ROLE OF GPS IN THE WEGENER PROJECT

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Abstract—In recent years, the Global Positioning System (GPS) has become a major tool for high precision geodesy. The precision is now better than 1 ppb. In this paper, the importance of GPS for the WEGENER project is highlighted. First, an overview of the GPS system is presented including a description of the development of its capabilities. One of the most significant developments of the past few years has been the establishment of the International GPS Service for Geodynamics (IGS). Thanks to its standards and products, the state-of-the-art in high precision GPS has been advanced considerably. Therefore, a summary of the goals and principles of IGS is presented next. This is followed by a compilation of the major GPS projects in Europe and its surrounding areas, since 1988. Most of these are not related to the WEGENER project, but it shows how much work has already been done. It also indicates the possible future role of GPS in WEGENER. Since all these projects are usually quite independent, they might benefit from the existence of a consistent, dense, accurate regional reference frame. This is exemplified by the success of IGS, which is based on an expanding global network of continuously operating permanent GPS stations. It provides a stable global reference frame, which makes it feasible to combine the results from independent field campaigns. In certain regions of the world the coverage is not yet optimal, however, and it is planned to further densify the IGS network. Therefore, it might be interesting to establish a dense regional GPS network in the general research area of WEGENER, which extends from Greenland to mid-Asia. This idea is promoted in Section 5 of the paper, where it is proposed to create such a network under the name of WEGNET, for WEGENER GPS Network. It would seek to establish new sites where none exist yet and to include existing stations that may already have been established for other purposes. Apart from providing a regional densification of IGS and a reference frame for WEGENER, the network may also yield valuable contributions to the monitoring of tectonic motions in the area and for studies concerning ocean and atmospheric loading.

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1. INTRODUCTION

In the early eighties, a new space geodetic technique emerged, based on the Global Positioning System (GPS). This is a space based positioning and navigation system, officially called NAVSTAR/GPS for NAVigation by Satellite Timing And Ranging/Global Positioning System, which has been developed by the U.S. Department of Defense over the last decade. The system will become fully operational in 1994. It consists of a network of 24 satellites in high earth orbits, which broadcast specially coded radio signals on two frequencies. These signals enable a user to determine his instantaneous position at any time and anywhere on the earth, with an accuracy of 5 to 150 m, depending on the sophistication of his receiver equipment. Originally, GPS was intended for military applications only, but since many simple, low-cost receivers have appeared on the commercial market, civil applications are now dominating the use of the system.

Still, many geodetic applications, in particular for geodynamics, require millimetre level accuracies, which is beyond the basic performance of the system. However, it was realized early on that by using the GPS signals in a differential mode, the accuracy of the relative position determinations could be increased substantially. This effect was bolstered by the addition of measurements of the phase of the carrier signals. Because of the very short wavelength of these signals (ca. 20 cm), the measurement precision could be increased to the millimetre level. For this purpose, special receivers were developed, which have been used successfully since the mid-eighties.

Initially, their application was limited to relatively small local networks, with a spacing between the receivers of about 100 km at most. The relative position determinations were accurate at the few parts per million level, equivalent to a few centimeters for the networks considered. Further improvements in the receivers, expansion of the GPS satellite constellation and, in particular, new developments in the data analysis techniques, boosted the accuracy to a level of a few parts per billion and at the same time increased the capabilities to regional and even global networks.

An important contribution to this accomplishment has been provided by the establishment of the International GPS Service for Geodynamics (IGS). Its purpose is to provide common standards for the acquisition of GPS observations and the subsequent data analyses, and to generate precise ephemerides for the GPS satellites together with other products, such as earth orientation parameters and GPS clock information. The service is based on a cooperative network of about 90 globally distributed stations equipped with high quality GPS receivers. It was initiated in 1989 by the International Association for Geodesy (IAG) and after a half-year test campaign in 1992, which turned into a pilot service, official operations started on January 1994. The benefits, which became clear even during the test phase, consist primarily of a tremendous improvement in the accuracy of the GPS ephemerides and the establishment of a rigorous global reference frame.

In the framework of the WEGENER-I project, which lasted from 1984 until 1991 and which focused primarily on the Eastern Mediterranean area, GPS has been applied for various purposes. First, it was used to support the reconnaissance activities for new SLR sites. After these had been constructed, a local control network was established around each of them, again with the help of GPS. Furthermore, several densification projects were carried out in a number of smaller sub-areas within the main region of interest of the WEGENER-I project. In these projects, the WEGENER SLR sites were frequently used as reference points. However, it was not until 1992, after the start of the WEGENER-II project, that all these SLR sites were simultaneously observed with high precision GPS receivers, during the first dedicated WEGENER-GPS campaign. The results of this experiment, which benefited greatly from the experimental products of the IGS test campaign that was going on at the time, were very encouraging and showed good agreement with the SLR results obtained so far.

The WEGENER-II project, described in this paper, has a wider scope and covers a much larger region than its predecessor (Wilson *et al.*, 1995). It roughly extends from Greenland to mid-Asia in the northern hemisphere. Clearly, it will not be possible to organize single GPS measurement campaigns that will cover this region with sufficient density. Besides, this is not necessary, since the major interest focuses on certain sub-areas, which may be served by their own high density networks. However, it is important to anchor all these sub-networks into one common reference frame. This may be achieved by establishing a relatively wide-spaced network of reference stations which are embedded in the global reference frame provided by IGS. Therefore, it is proposed to set up a permanent network of continuously operating GPS stations for WEGENER.

This network, which has been dubbed WEGNET, for WEGENER GPS Network, will partially overlap with the existing IGS network, and may be organized according to the same philosophy. It is envisaged that it will include a selection of the stations of national or local reference networks, many of which already exist or are in various stages of development. It has the added advantage of also connecting these local networks to the global reference frame. This starting configuration will have to be augmented by additional stations in those areas where nothing exists or has been planned yet, in order to obtain a more-or-less homogeneous coverage of the entire WEGENER-2 region of interest. The EUREF commission of the IAG has plans for a similar network in Europe, which may be integrated with WEGNET. The idea will be further expanded in the final section of this chapter on GPS.

2. GPS: AN OVERVIEW

This synopsis of the past ten years will provide a broad overview of Global Positioning System (GPS) applications for precision geodetic investigations and describe in elementary terms the GPS technique for precise measurements. There has been incredible growth and expansion of GPS applications, and it is challenging to keep pace with the varied precision uses of GPS, which include the following:

- Experiment networks for crustal deformation or tectonic motion observed episodically and recurring every one to two years;
- Deployments of GPS receivers to measure co-seismic displacements and post-seismic relaxation;
- Global network of continuous, near real-time GPS data necessary to determine the precise orbits of the GPS satellites, to generate earth orientation products, to extend the International Terrestrial Reference Frame (ITRF) or to plot global ionospheric maps;
- Continuously operating dense arrays of receivers that are used to monitor motions within a smaller active region;
- Rapid static surveys (RSS) to quickly observe many points along a profile for very dense sampling of precise surface positions;

- Air to ground GPS differential tracking for photogrammetry, Synthetic Aperture Radar (SAR), and Remote Sensing instrument locations;
- Seafloor geodesy that uses GPS to position sea-surface buoy instruments which concurrently measure precise distances to ocean bottom transponders (eventually to measure ocean spreading center rates);
- Low Earth Orbiter (LEO) tracking which uses a ground-based tracking network and an on-board GPS flight receiver, such as on the TOPEX/Poseidon satellite;
- Atmospheric occultation studies using GPS flight receiver observations to recover temperature, pressure and water vapor profiles as demonstrated by the GPSMET experiment.

This evolution of GPS has been fascinating and will no doubt continue to be diverse for the foreseeable future.

2.1. *The Global Positioning System*

The NAVSTAR (Navigation Satellite Timing and Ranging) Global Positioning System was developed primarily for worldwide navigation, both civilian and military. The NAVSTAR GPS Program is under a Joint Program Office that includes representatives from different branches of the military and is managed by U.S. Air Force. The GPS has three components: Space, Control and User (Bagley and Lamons, 1992). The Space or satellite segment has 21 space vehicles (SVs) optimally placed in six orbital planes and three active spares. The satellites are in circular orbits with 12-h periods and have an inclination of 55° (the Block I satellites were launched with a 63° inclination). Table 1 summarizes the basic characteristics of the satellite constellation and its status in late 1995.

The satellites transmit signals at two L-band radio carrier frequencies: L1 at 1575 MHz and L2 at 1227 MHz (Spilker, 1980). The satellites also transmit a Navigation Message that provides users with the Broadcast Ephemeris, the Almanac, satellite clock information, time (UTC), satellite health, and ionospheric parameters. Modulated on the L1 carrier is the coarse acquisition code, or C/A code at 1.023 MHz, for rapid acquisition of the signal and the navigation message. Each of the L-band carriers is also modulated with the so-

Table 1. GPS constellation basic characteristics

Block I (Development and proof of concept)
11 Space Vehicles (SVs or satellites), 10 successful launches
Status, late 1995: 1 remains operational
SA/AS not enabled on Block I SVs
$i = 63$

Block II (Operational satellites)
21 SVs, 3 active spares, 28 produced
Status, late 1995: all 24 are operational (since early 1994)
$i = 55$
4 satellites in each of 6 orbital planes

General
Nearly circular orbits
Altitude = 20 200 km (relative to the surface of the earth)
Satellite ground tracks repeat every sidereal day (23 h 56 min)

Table 2. GPS signal relationships

Band	Frequency υ (MHz)	Wavelength λ (m)	Period τ (ns)	Ratio of frequency to P1 (exact)
C/A	1.023	293.20	977.500	0.1
P1, P2	10.230	29.32	97.750	1
L1	1575.420	0.19	0.635	154
L2	1227.600	0.24	0.815	120

called P-code, for precision or protected code. To discriminate between the measurements at the two carrier frequencies, the P-code signals are labelled P1 and P2. The relationships between the various GPS signals are summarized in Table 2.

Operational limitations have been placed on the use of the system, one of these is 'SA' or selective availability, which has two components: the degradation or introduction of errors into the Broadcast Ephemeris which limits real-time position/velocity accuracies and 'dithering' of the satellite clock. Another limitation is 'AS' or Anti-Spoofing, in which the P-codes are encrypted with the so-called 'Y-codes'; access to the Y-codes is restricted to military purposes. Geodetic-type receivers make use of the carrier signals themselves to achieve a much higher measurement precision than is possible with the basic system. They are also capable to partially circumvent the AS limitation by tracking in a so-called codeless mode, which is based on cross-correlation of the Y-code on both frequencies.

The Control Segment is responsible for the operation of the satellites and uses the 10-station tracking network of the Air Force and the Defense Mapping Agency. The Air Force stations are located at Hawaii, Colorado Springs, Ascension Island, and Diego Garcia; and the Defense Mapping Agency stations are at Quito, Buenos Aires, Hermitage (U.K.), Bahrain and Smithfield (Australia). The Master Control Station in Colorado Springs directly controls and uploads information to the satellites.

The User Segment is anyone with a GPS receiver, antenna and some processing/display capability that can produce either real-time estimates of the absolute positions, velocities and time, or who processes and analyzes the data at a later time. In most cases, the geodetic applications discussed in this overview require long tracking intervals (multiple 24-h periods) and post-processing of data from two or more stations.

2.2. *Basic geodetic principles for GPS relative positioning*

As already mentioned, geodetic-type receivers make use of the carrier signals themselves. The measurement precision is extremely high (< 1 mm), but due to the short wavelength of the signals, the measured ranges are ambiguous. Besides, they are affected by all kinds of errors such as delays due to the troposphere, both wet and dry, the ionospheric delays, delays due to satellite or receiver clock offset, and other sources of error such as multipath near the receiver antenna or at the satellite, phase center variations of the antennas, etc. It has been shown that the effect of these errors can be greatly reduced by processing the observations in a differential mode. This is a viable technique, since after all, in many geodetic problems, one is primarily interested in coordinate differences between points, and these can be easily obtained from the measurement differences.

By differencing the measurements of two receivers observing the signals from the same satellite, the satellite clock error will cancel, as well as most of the tropospheric and ionospheric delays, provided that the receivers are not too far apart. A simple graphic of this geometry is shown in Fig. 1. The resulting observations are called single differences.

In the next step, the single-difference observations of different station–station–satellite pairs may be combined to eliminate or reduce the other errors due to station clocks, multipath and phase center variations. The geometry of these so-called double-difference observations is depicted in Fig. 2. From a set of double-differenced observations with a variety of satellite–receiver geometries, all components of the baseline between the two stations can be estimated, including the cycle ambiguities in the measurements. This concept assumes that the GPS orbits, are available. The accuracy of these orbits will then be a dominant factor for the accuracy of the baseline results. When the technique is applied to complete networks, the orbit parameters may also be adjusted by using so-called fiducial stations with accurate a priori coordinates. Another possibility is to use global networks.

To achieve the highest possible accuracy it is also important to apply the best available models for all the potential error sources. The ionosphere, however, represents a major error source which is difficult to model, because it is highly unpredictable. A solution for this problem is to combine the measurements taken on both carrier frequencies. It can be shown that special linear combinations exist which completely remove the first order ionospheric delays from both the carrier phase and P-code ranges. Although they are much less precise, the latter are often also used in the analyses because they ease the data pre-processing and because they stabilize the parameter estimation process.

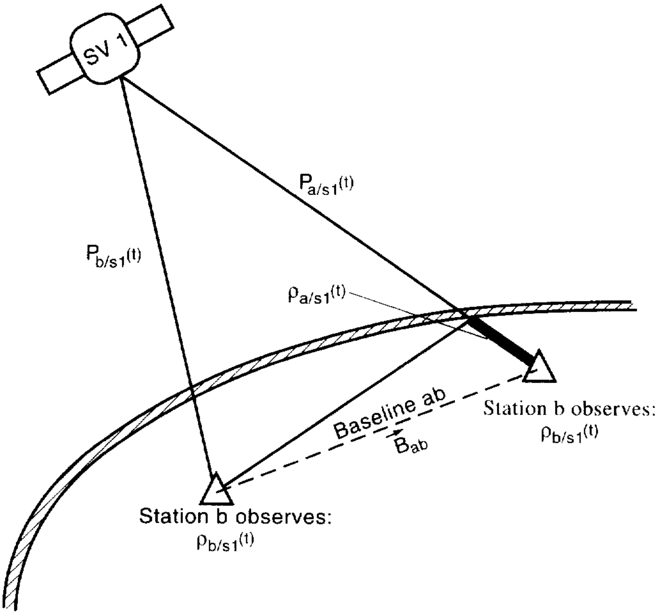

Fig. 1. Single-difference geometry.

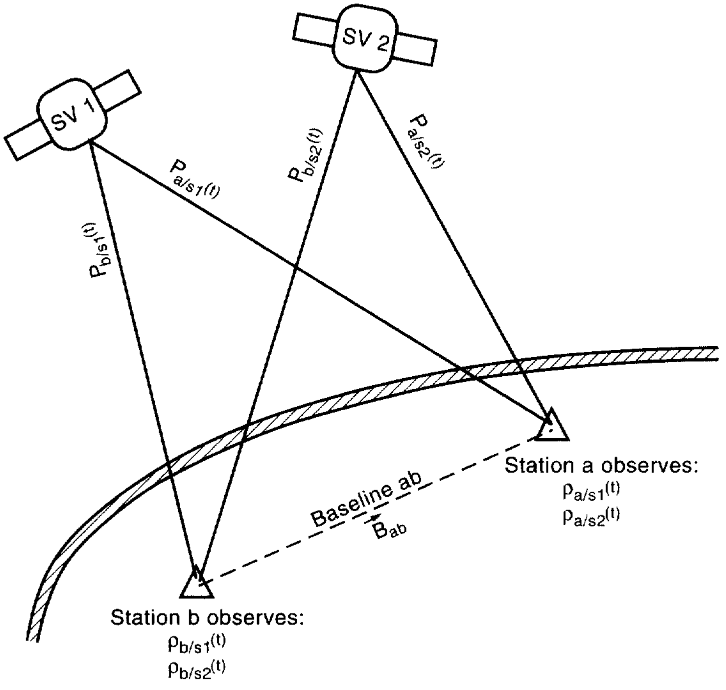

Fig. 2. Double-difference geometry.

2.3. *Achievements of the past ten years*

An attempt to capture the significant highlights of GPS developments and applications is shown in the timeline of Fig. 3. The timeline stretches from 1983, when GPS geodetic applications were 'born', to early 1994. The major components of the timeline are the satellite system, GPS receivers, data processing, accuracy, field experiments, and tracking networks. This schematic will hopefully help to put a perspective on the past decade by plotting key achievements in each area.

The satellite section lists the basic information of the GPS constellation, and basically shows the increasing number of satellites with time. One can recall the period in the late eighties when there were few launches and the difficulty this caused in planning the optimum '4-satellite' mutual-visibility observing sessions.

The section on GPS receivers represents those that were used in numerous geodetic campaigns, and does not attempt to list all receivers, just the most familiar ones. The commercial price for a quality geodetic, dual-frequency receiver has decreased from about US $150 000 for the TI-4100 in 1984 to roughly US $25 000 for the latest generation of P-code receivers. We will certainly see superior quality GPS receivers available for less than US $10 000 by the year 2000.

Processing of the GPS data to produce precise orbits and positions is performed by an elite class of software, most originally developed in the early eighties, many with their roots in Very Long Baseline Interferometry (VLBI) and in Satellite Laser Ranging (SLR). These software packages have undergone continual improvement and upgrades and most have

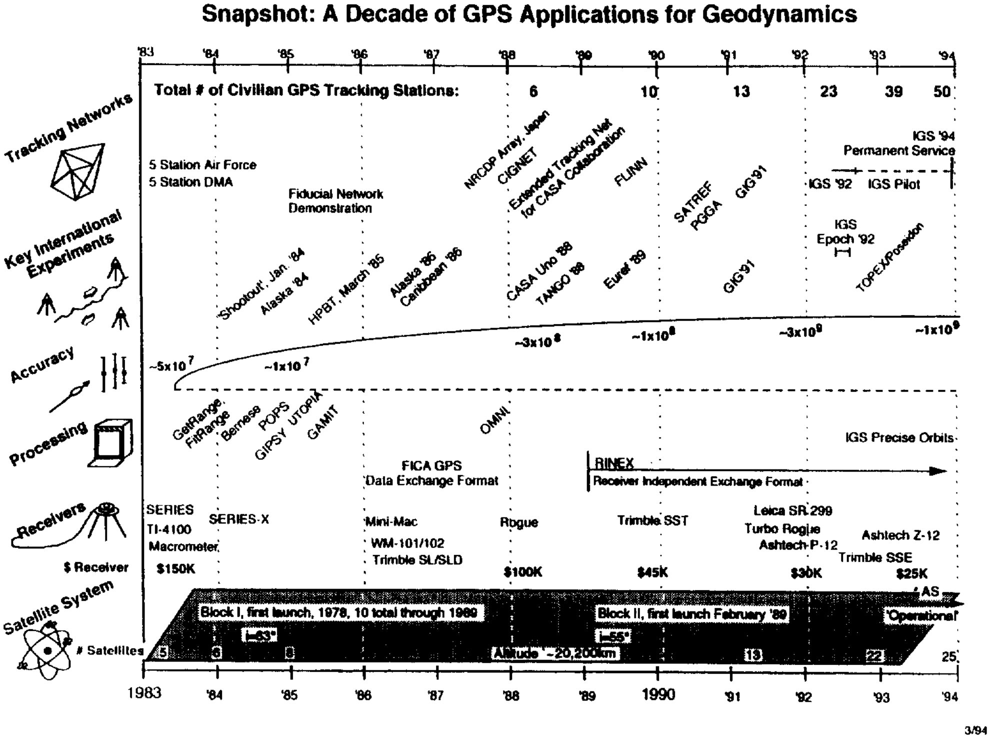

Fig. 3. Snapshot: A decade of GPS applications for geodynamics.

also been used by other institutions or universities for research and development. A key issue in the processing of GPS data is a standard data exchange format that interfaces between different GPS receivers and the various software packages. The FICA format, developed and maintained by Applied Research Laboratories of the University of Texas eventually was replaced by the RINEX format (Receiver Independent Exchange Format) developed at the University of Bern, Switzerland.

The improvements in the satellite constellation, GPS instrumentation and processing have had a direct influence on the accuracies achieved by GPS analysis groups. In 1984, precision at the level of a part in 10^7 was considered fantastic for the new GPS, and was also quite possible when using the precise ephemerides produced by the Naval Surface Weapons Center (now the Naval Surface Warfare Center, NSWC). Today the Broadcast Ephemeris has orbits that are accurate at the few to 5-m level ($\approx$1–2 parts in 10^7), while the precise ephemerides generated by the Analysis Centers of the International GPS Service for Geodynamics are accurate to the 10-cm level and better ($\approx$3–5 parts in 10^9) (Beutler and Brockmann, 1993).

The successful deployment of GPS experiments and tracking networks were key to this evolving system. One of the earliest experiments was the receiver intercomparison of January 1984, coordinated by the U.S. National Geodetic Survey. The 'Shoot-Out', as it was referred to by participants, was conducted primarily in Southern California with the resulting GPS baseline vectors compared to those of VLBI. The final report concluded that GPS was a viable geodetic measurement tool.

The next major test, in March 1985, was the High Precision Baseline Test (HPBT'85). This was a test conducted at 10 stations in the US, many collocated with VLBI and using 15 dual frequency geodetic receivers. The data set that was generated was analyzed by a number of analysis groups and the 'Fiducial Concept' was demonstrated (Davidson *et al.*, 1985). This technique constrained the GPS positions to VLBI at three stations in order to constrain the precise orbits and define a terrestrial GPS reference frame aligned with prior VLBI results.

The applications of GPS to study the dynamics of the earth led to an incredible demand for GPS receivers and experimental support. Regional campaigns began to mushroom. One of the early, key international experiments was CASA Uno '88 (Central and South America '88). This experiment brought together nearly 30 different international agencies participating in the effort to perform the first-epoch geodetic measurements for monitoring Central and South American crustal deformation (Neilan *et al.*, 1990). Nearly 45 receivers were deployed in 13 different countries. This was the first experiment that used a nearly global distribution of tracking stations in order to generate the precise orbits necessary to reduce the scientific dataset. CASA Uno proved to be successful from the scientific aspect as well as for demonstrating the benefits of a robust global tracking network.

Another major international experiment was EUREF-89, the first campaign for the determination of transformation parameters between the national geodetic networks of all countries on a subcontinent. It involved more than 60 receivers from four different manufacturers and about 100 sites in 17 Western European countries; 25 of these stations were collocated with VLBI or SLR.

The top section of the timeline in Fig. 3 represents the various tracking network efforts of the last ten years. CIGNET (Coordinated International GPS Network), was an early activity coordinated by the NGS and soon augmented by many international partners (Mader *et al.*, 1989). NASA's FLINN program focused on implementing a standard P-code tracking network to form the core of an eventual network of geophysical observatories (Neilan *et al.*, 1990). The first regional continuous array was installed in Japan in 1987 by the National Research Center for Disaster Prevention (NRCDP) and has grown from 10 to more than 100 stations. In 1990, a start was made to set up a similar network in southern California to monitor the crustal deformations in that area. This Permanent Geophysical GPS Array (PGGA), is now part of the Southern California Integrated GPS Network (SCIGN). At present it consists of 25 stations, but it is planned to expand it to over 200 stations. This is a much more economical way to monitor the deformations in such hazard areas than campaign type experiments.

Finally, 1991 was a pivotal year for tracking networks in another regard: it marked a major event which would later lead to the establishment of IGS. This important development will be further discussed in Section 3.

3. THE INTERNATIONAL GPS SERVICE FOR GEODYNAMICS (IGS)

At the 20th General Assembly of the International Union of Geodesy and Geophysics (IUGG) in Vienna in August, 1991, Resolution No. 5 recommended that the concept of the IGS be explored over the next 4 years. As a first activity, in 1992, a 3-month test campaign (from 21 June to 23 September 1992) was conducted. This campaign was successful beyond all expectations and is considered as the proof of concept for the IGS. The test campaign was followed by the IGS Pilot Service (starting 1 November 1992). The official IGS started on 1 January 1994.

Since the beginning of the IGS test operations on 21 June 1992, a continuous set of highly accurate daily GPS orbits and earth rotation parameters has been available from individual processing centers. The accuracy of the products was improved from, initially, about 1 m for the orbits and 1 mas for the earth rotation parameters (ERPs) to about 20 cm and 0.2–0.4 mas, respectively, at present. Since 1 January 1994, a combined IGS orbit has been available to the scientific user community. It is an accurate, stable, and reliable product which allows high precision geodetic positioning. Since 1995, efforts have been under way to produce combined station coordinate solutions for the global network.

3.1. *Objectives, structure and development of the IGS*

The objectives of the IGS are specified in the Terms of Reference (Mueller, 1993a):

> 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... 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 are used by the IGS to generate the following data products:
>
> - high accuracy GPS ephemerides,
> - earth rotation parameters,
> - coordinates and velocities of the IGS tracking stations,
> - GPS satellite and tracking station clock information,
> - ionospheric information, etc.

The basic ideas about IGS were already conceived in 1989. According to (Mueller, 1993b):

> 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 observations as well as the subsequent data analyses were not based on common standards; thus the geodynamic interpretation of the results ... could not be trusted.

These ideas soon led to the establishment by the International Association for Geodesy (IAG) of a special working group, which was later redesignated as the 'IGS Planning Committee'. The task of this group was to formulate the terms of reference for such a service, to organize a test campaign in 1992 and to present a proposal to the IAG for the establishment of the service after the campaign. On 1 February 1991, the 'Call for Participation' was issued by this group, soliciting international contributions to the test campaign. Eventually, the IGS Planning Committee received a positive response from nearly 120 different agencies.

At the 20th General Assembly of the IUGG in Vienna, August 1991 the IGS planning group was restructured and renamed the 'IGS Campaign Oversight Committee'. This committee organized the 1992 IGS Test Campaign, which was scheduled from 21 June to 23 September 1992. It was to serve as the proof of concept for the future IGS. The demonstration was highly successful (Beutler, 1993). The data from the tracking stations were transferred within 3 days to three Global Data Centers from where they were accessed by eight Analysis Centers (Table 3). These used the data to compute precise orbits and ERPs, which were made available to users within two to three weeks. An important aspect in achieving this short turnaround time was the extensive use of Internet for both the data transfer and the dissemination of the orbits. More background information about this early phase of IGS may be found in Mueller (1993b) and Mueller and Beutler (1992).

In order to maintain momentum, the IGS Pilot Service was approved by participants in October 1992, allowing the global tracking network to continue, expand and improve operations without interruptions after the test campaign. Approval for the permanent IGS was given by the IAG Executive Board at the General Assembly of the International Association of Geodesy (IAG) in August, 1993 in Beijing, China. The permanent service was recognized to begin on 1 January 1994. For the overall coordination and management of IGS the IGS Central Bureau was established. It is located at the Jet Propulsion Laboratory (JPL) in Pasadena, California and funded by the National Aeronautics and Space Administration (Liu *et al.*, 1994). Supervising the whole organization is the Governing Board (GB), the successor of the IGS Campaign Oversight Committee.

Since the initial IGS campaign of 1992, the network has increased from 21 stations to over 90. Fig. 4 shows the current tracking network. Also indicated are planned, future stations. For most stations, the availability of tracking data is currently within one day (for the previous 24-h dataset) and for products generally within one to two weeks. The processing is based on a weekly cycle, although daily solutions are also generated. There are plans to improve the turnaround time even further to less than 3 days. At present, seven of the original eight Analysis Centers are still active. They produce estimates for the ERPs, GPS clock corrections and, of course, precise GPS orbits. Since 1994, an 'official' IGS-combined precise GPS ephemeris is produced by the Analysis Center Coordinator at the Natural Resources of Canada. It is available via the IGS Global Data Centers and at the IGS Central Bureau, which maintains an on-line information system that can be accessed by anyone. In 1995, a start has been made to develop a system to produce global station coordinate solutions at regular intervals.

Table 3. IGS Global Data Centers (D) and Analysis Centers (A)

Center	Institute	Operational
CODE	(A) at Astronomical Institute, Bern, Switzerland[a]	Since 21 June 1992
EMR	(A) Energy, Mines and Resources, Canada	Since September 1992
ESOC	(A) European Space Agency, Germany	Since 21 June 1992
GFZ	(A) Geoforschungszentrum, Germany	Since 21 June 1992
JPL	(A) Jet Propulsion Laboratory, USA	Since 21 June 1992
NOAA	(A) Natl. Oceanic and Atmos. Admin., USA	Since March 1993
SIO	(A) Scripps Inst. of Oceanography, USA	Since 21 June 1992
UTX	(A) University of Texas at Austin, USA	21 June–23 Sept. 1992
CDDIS	(D) Goddard Space Flight Center, USA	Since 21 June 1992
IGN	(D) Institut Geographique National, France	Since August 1992
SIO	(D) Scripps Inst. of Oceanography, USA	Since 21 June 1992

[a] Collaboration of the Astronomical Institute, Bern, the Institut Geographique National, the Institut für Angewandte Geodaesie, and the Swiss Federal Office of Topography.

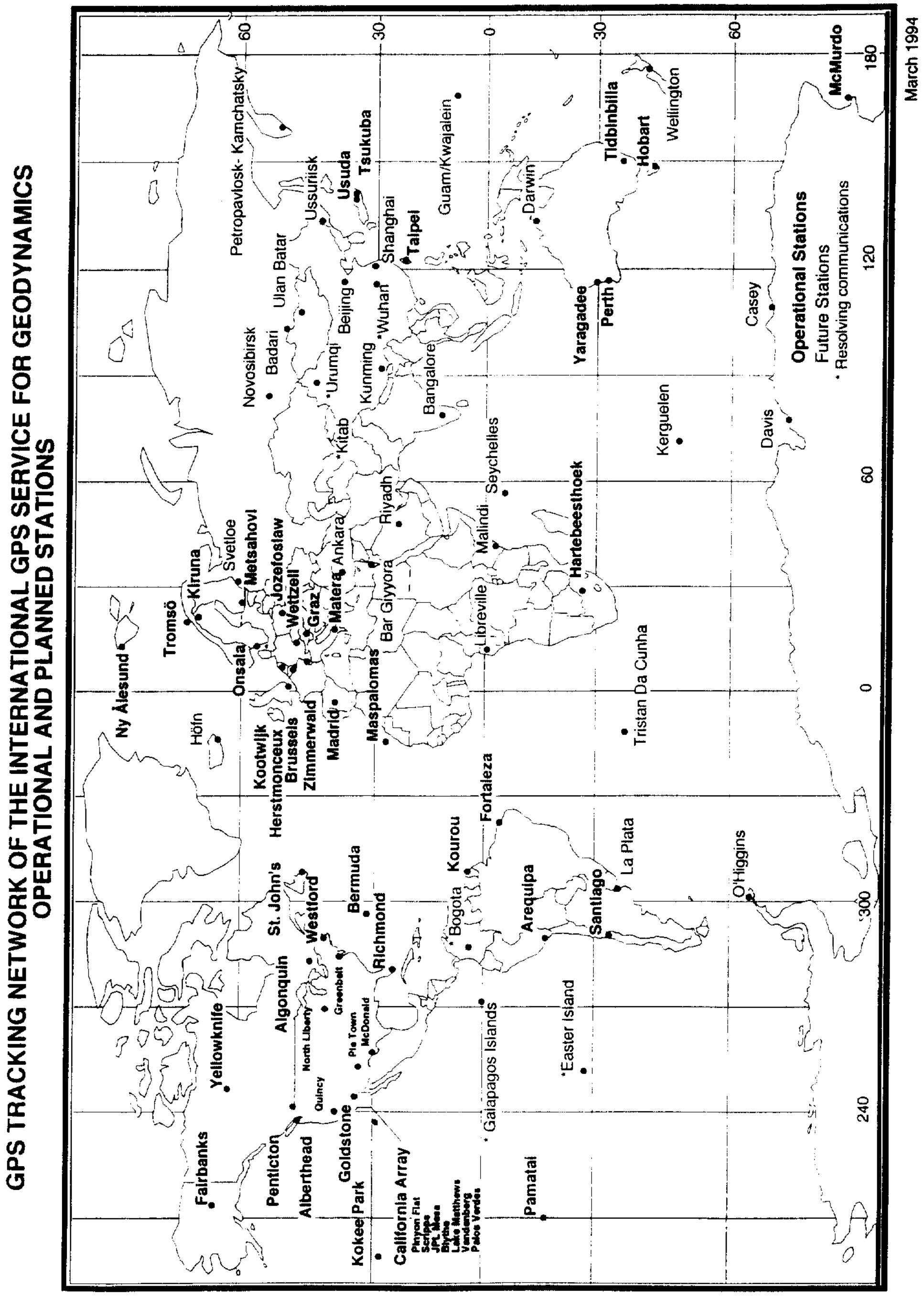

Fig. 4. Distribution of current and future (potential) permanent IGS sites.

3.2. *Quality of IGS products*

Today the IGS processing is based on a network of about 90 permanent GPS sites (Fig. 4). To provide a stable reference frame, all processing centers keep the coordinates of (at least) 13 so-called Core Stations (almost) fixed on their IERS values (currently ITRF-93). Others (about 20–30 stations, which may be different for each analysis center) are estimated in the routine processing. In addition all the centers have the capability (or are developing it) to produce so-called 'free network' solutions, where, based on the technique of stacking normal equation systems, all station coordinates and velocities are freely adjusted, and the IERS reference frame is maintained through so-called system conditions (the most popular one is the no-net-rotation condition). Such free solutions are published on an annual basis (e.g. Charlot, 1993). They help to improve the ITRF regularly together with the results of the other space techniques.

The series of earth orientation parameters of the IGS processing centers are frequently analyzed by the IERS Central Bureau (Feissel, 1993; Gambis *et al.*, 1993) and by the IERS Rapid Service Sub-bureau (McCarthy, 1993). The precision of the individual series today approaches a level of about 0.3 mas for the position of the pole on the earth's surface, and of about 0.04 ms for the length of day. During the 1992 IGS Test Campaign, the corresponding values were more like 1 mas and 0.10 ms.

To check the quality of the orbits computed by each analysis center, since 1 November 1992, weekly comparisons have been made of the individual IGS daily orbit files by Professor Clyde C. Goad, the analysis center coordinator during the IGS Test Campaign and the IGS Pilot Service. These comparisons are made through 7-parameter Helmert transformations between the orbits generated by each pair of analysis centers. From the a posteriori rms errors per satellite coordinate of all these transformations it is possible to derive an rms error per satellite coordinate for each center. Fig. 5 shows the monthly means

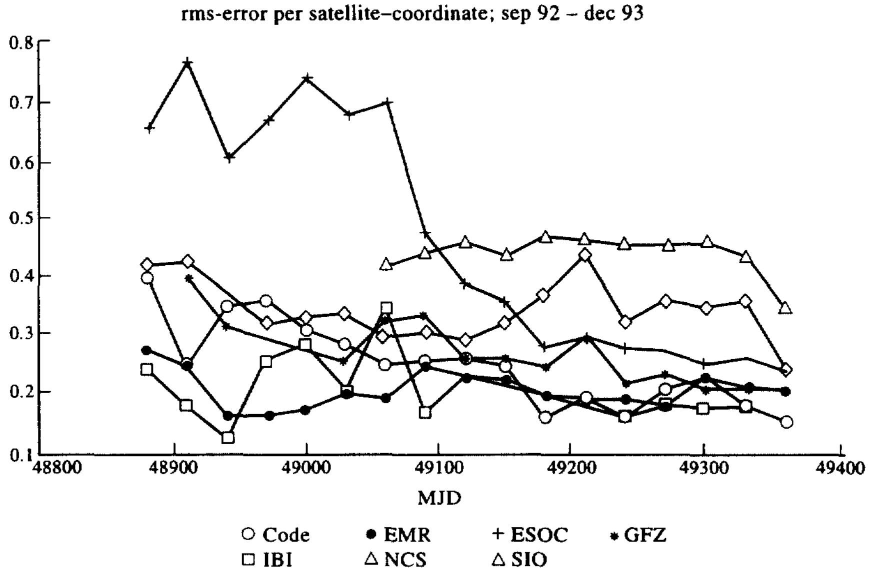

Fig. 5. Development of the orbit quality of the IGS Processing Centers from 1 November 1992 to 31 December 1993. The center-specific error per satellite coordinate serves as a measure for the orbit quality.

of these errors. It is evident that in the course of time the orbit accuracy has improved considerably, clearly converging to a level of 10–30 cm.

Since 1 January 1994, with the official start of IGS, the 'Natural Resources of Canada (NRC)', (former 'Energy, Mines, and Resources Canada') is now responsible for the production of the combined, official IGS orbit. The method used at present is the weighted average scheme as suggested by Springer and Beutler (1993), which was later further refined (Beutler *et al.*, 1993). The orbit dynamics method, also described in this article, is applied in a 'pre-processing step' to detect and edit gross errors. This method uses the satellite positions from the orbits computed by the analysis centers as pseudo-observations in an orbit adjustment step.

Fig. 6 shows the high degree of consistency (typically below the 25 cm level) of the individual orbit series with respect to the combined orbit. Needless to say, such a combined orbit is not only of comparable or better accuracy than that of every individual series, but it is also more reliable than each individual series. The combined orbit is particularly easy to use because it refers to the official pole series as produced by the IERS.

Also, since 1994, the satellite clock solutions of those IGS Analysis centers providing satellite clock estimates, are combined in a fashion similar to the orbit combination. The combined clock solution is included in the official IGS orbit files.

3.3. *Significance of IGS for WEGENER*

The significance of IGS for the WEGENER project is manifold. In the first place its products have been and will be used extensively in data analysis of dedicated campaign-type experiments. Furthermore, it provides a stable global reference frame which enables the connection of independently determined regional networks. Also, it has set the standards

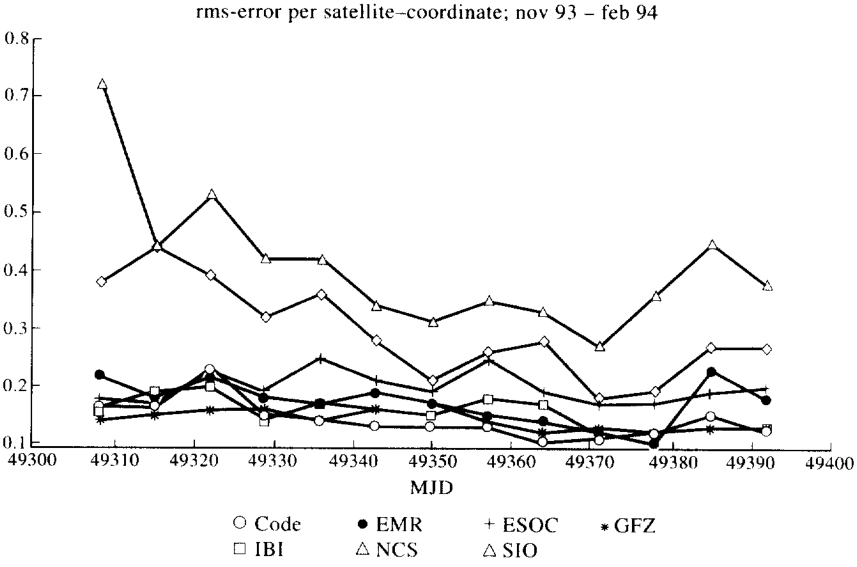

Fig. 6. The RMS errors per satellite coordinate of the contributing IGS Processing Centers to the combined IGS orbit (weekly means, extracted from the IGS Report Series).

for further densification. A proposal for such an effort in the framework of WEGENER is discussed in Section 5.

4. GPS PROJECTS IN THE WEGENER AREA

Until the start of the WEGENER-II project which began in 1991, there had not yet been any formal GPS measurement activities in the framework of WEGENER other than the measurement of some small local networks around the WEGENER mobile SLR points for site stability control. During that time-frame, the second half of the eighties, the GPS satellite constellation was not yet complete, good-quality receivers were still expensive and scanty and data analysis techniques were still maturing. However, at the same time, and independently from WEGENER, individual groups and combinations of cooperating institutes from Europe and the US were already pioneering with the GPS technique in smaller sub-areas of the original research area of the WEGENER project, the Eastern Mediterranean region. Also, within the framework of EUREF (see below), the first initiatives were taken to cover the whole European area with GPS. Furthermore, many new plans for future measurement campaigns in geodynamically interesting sub-regions of the extended WEGENER-II research area were being conceived, and permanent GPS reference networks started to emerge in many countries. Last but not least, the newly established IGS started to introduce commonly accepted standards and catalyzed the acceptance of GPS as a superior space-geodetic technique for geodynamics research.

Since the December 1992 WEGENER-II conference, where it was attempted to establish the status of the various measurement techniques and to define their role in achieving the scientific goals of the project, the developments in GPS have been extremely fast. Many institutions now possess large quantities of high-quality GPS receivers, which they use for intense measurement campaigns on regional scales, both inside and outside the current WEGENER area of interest. Also, new agreements for cooperation are now leading to expansion of the GPS networks to the vast area of the CIS, which was hitherto mostly terra incognito in terms of precise positioning. Most of the observation campaigns are still carried out in the framework of separate research projects, which do not specifically fall under the umbrella of WEGENER. Two noticeable exceptions were the dedicated observation campaigns in 1992 and 1994, organized by IfAG, in which most of the WEGENER/MEDLAS sites were observed with GPS for the first time in a consistent way. However, it will be clear that the individual results of all the projects are beneficial for the overall goals of the WEGENER project and it is expected that the data will eventually be used for comprehensive deformation studies.

Therefore, in the following, an overview will be given of the major projects that involve GPS observations, which have been carried out until the middle of 1995. Possible future re-occupations and new projects will also be indicated. It is emphasized that this overview is by no means exhaustive. It concentrates on the major projects as far as they are known to the author. However, there may be many more projects and plans which could be relevant for the WEGENER investigations. It is suggested that this information should be included in some sort of database and to make that available to the scientific community. Any interested investigator could then contact the principal investigator of the project for further information.

The overview consists of a brief description of each of the projects. It starts with the overall projects, which cover a larger region. Next, it focuses on the Eastern Mediterranean region, which was the primary study area of the WEGENER project until 1991. Then, the area of interest moves via the central Mediterranean to the western end of the Eurasian plate. Subsequently, a few projects not related to the Eurasia/Africa/Arabia convergence are discussed. The overview concludes with two projects, especially concerned with the vertical component of some geophysical processes.

4.1. *EUREF*

The IAG subcommission for the European Reference Frame (EUREF) has organized several GPS measurement campaigns in Europe to connect the various national and regional networks and to establish a common European reference frame. The first campaign took place in May 1989, and comprised about 100 sites, including many national geodetic first order points and most of the well-established SLR and VLBI sites. It may be considered as a pilot project, since it was the first attempt to do such a large-scale GPS project in Europe and because the circumstances were far from optimal: the GPS constellation was not yet complete and a mix of four different GPS receivers and antenna types was used. Also the network was rather inhomogeneous and left large areas uncovered. Therefore, several densification projects were organized in later years, covering Great Britain (October 1992), Cyprus (January 1993), Luxembourg (March 1994), Croatia and Slovenia (19 sites in May–June 1994) and Denmark (August–September 1994). Further activities are foreseen and future campaigns have been planned, with particular emphasis on the vertical component. Also, EUREF has started to implement and coordinate a network of permanent GPS stations, which represents the regional densification for Europe of the global IGS network.

4.2. *GIG'91*

In February–March 1991, the GPS IERS and Geodynamics experiment (GIG'91) was organized. It was the first attempt to demonstrate quick transfer and processing of global tracking data, resulting in near real-time products such as precise GPS orbits and Earth rotation parameters. The tracking network consisted of 23 globally distributed stations of which seven were located in Europe. It may be considered as the prototype of the IGS network. In parallel with this effort, many regional densification campaigns were organized all over the world. It is estimated that valuable observations have been collected from about 25 additional stations in Europe alone. The only problem is that a large variety of receivers and antennas was used.

4.3. *WEGENER/GPS*

The first dedicated GPS observation campaign for the whole WEGENER/MEDLAS network took place in July–August 1992. It was organized by the Institute für Angewandte Geodäsie, in cooperation with Delft University of Technology (DUT). The network comprises all the sites in the Eastern Mediterranean area, which have been occupied by mobile SLR since 1986, plus a few points of the fixed European SLR network. A total number of 17 sites was observed by Trimble SST receivers during a period of 6 days. The measurements allowed the first direct comparison of the SLR and GPS coordinate solutions in this area and they proved to match extremely well (Springer *et al.*, 1994). In July–August 1994, in a second campaign, most of the network (11 sites) was re-observed by Trimble SSE receivers. Apart from revealing the broad-scale tectonics in this region, the network also provides a valuable reference frame for several densification projects being carried out in this area by various groups.

4.3.1. *Turkey and Caucasia*—This area is the scene of some of the most active tectonic processes in the region. It is the collision zone of two major tectonic plates, i.e. the Eurasian and the Arabian plates. The resulting 'escape' of the Anatolian block to the south west and its counterclockwise rotation cause large earthquakes in the whole region and in particular along the North and East Anatolian faults. This has prompted several investigators to study the kinematics in this region by means of GPS observations. In a coordinated effort, since 1988, various GPS campaigns have been organized in western and eastern Turkey by MIT, IfAG and Durham University, in cooperation with the Turkish Union of Geodesy and Geophysics (TUJJB). In 1991, the activities were expanded to the Caucasus where a network of 10 stations was established by a group including the Institute of Physics of the Earth (IPE), Indiana University (IU) and MIT. In total, the integrated network now includes about 80 sites, which was observed as a whole for the first time in 1994. Further campaigns are planned in 1996 and 1998.

4.3.2. *Marmara Sea project*—This project, initiated by the ETH Zürich, focuses on the active earthquake belt of NW Anatolia, extending from the western part of the North Anatolian Fault Zone (NAFZ) to the Aegean extensional province (Straub *et al.*, 1995). It is intended to investigate the complex tectonic activity in this region. A dense network consisting of 52 sites has been observed during three measurement campaigns in 1990, 1992 and 1994.

4.3.3. *Central Greece project*—This project (Billiris *et al.*, 1991; Denys *et al.*, 1995) is closely tied to the West Hellenic Arc project. Several common stations serve as a connection between the projects. In 1988, a GPS measurement campaign was carried out to re-occupy 15 stations of an almost 100-year-old triangulation network. The main goal of the project was to characterise neo-tectonic strain in this particular area of the Eastern Mediterranean deformation zone. The network was extended to 66 stations in follow-on campaigns which took place in 1989, 1991 and 1993. The project was a major collaborative venture between the Universities of Newcastle, Nottingham and Oxford in the UK, NTU Athens and ETH Zürich.

4.3.4. *Aegean GPS project*—The aim of this project is to study the process of diffuse back-arc extension taking place in the Aegean Basin. To measure this, 29 sites have been selected, making up a network which quite nicely covers the gap between the Central Greece network in the west and the western Turkish network in the east. Many sites are located on islands in the Aegean Sea. The first campaign, in September 1988, covered the southern half of the network, while the northern half was observed for the first time in 1989. A complete re-occupation of the full network took place in 1992. The project is a cooperative effort of Lamont-Doherty Geological Observatory (LDGO) in the US, NTU Athens and IfAG, with assistance of MIT and UNAVCO).

4.3.5. *West Hellenic Arc project*—An important area to understand the kinematic processes at work in the Eastern Mediterranean is Central and Western Greece, at the edge of the Hellenic arc, in particular its western end. It is a region where high tectonic activity (south-west Greece) meets moderate tectonics (Ionian Islands, Italy). To study the fine structure of deformations in this area, a densification project was started by ETH Zürich in cooperation with NTU Athens (Zerbini *et al.*, 1994). The network comprises 30 sites, mainly in SW Greece and the Ionian Islands and a few in SE Italy. So far, four measurement campaigns have been carried out in 1989, 1991, 1993 and 1994.

4.3.6. *WHAT A CAT project*—In 1986, the University of Bologna and the Deutsches Geodätisches Forschungsinstitut (DGFI) set out to establish a control network in the southeastern Tyrrhenian Sea to observe the compressive stresses across the Calabrian Arc due to the collision of the African and Eurasian tectonic plates. This project became known as the Calabrian Arc Project, and in 1987 the first measurement campaigns took place during which nine sites were occupied, albeit with a mix of single- and dual-frequency GPS receivers. In 1988 the network was expanded with eight additional sites covering the Central Mediterranean in the triangle Cagliari, Lampedusa, Matera, this time with only dual-frequency receivers. In June 1990, the complete network was reobserved, including a few new sites bringing their total number to 20. During this campaign, a connection was also established with the network of the West Hellenic Arc project. This cooperation resulted in the creation of the new 'West Hellenic Arc Tectonics and Calabrian Arc Tectonics' (WHAT A CAT) project (Kahle *et al.*, 1993), in which the Calabrian Arc Project was absorbed. The complete network has considerable overlap with the separate West Hellenic Arc Project. Dedicated measurement campaigns were organized in 1992 and 1994, the last one involving 43 sites.

4.3.7. *Transatlantic network for geodynamics and oceanography* (*TANGO*) *project*—The south-west tip of the Eurasian plate is actually on a triple junction with the African and the North American plate. It is a complex deformation region situated near the Archipelago of the Azores. Since 1988, four major GPS campaigns have been carried out under the direction of the Observatorio Astronomico of the University of Oporto in Portugal. The networks of the campaigns in 1988, 1991 and 1994, under the names TANGO-1, TANGO-2 and SUPERTANGO, included stations on all (??) islands of the Azores. In addition, various sites on the islands of Madeira, Bermuda, Guadeloupe and Martinique were occupied as well as on the Portuguese and Spanish mainland, the Canary Islands and Ceuta. In 1993, only a partial reobservation of the Azores network took place during the AZORES-93 campaign.

4.3.8. *BIFROST project*—As reflected by its title, 'Baseline Inferences for Fennoscandian Rebound Observations, Sea-level and Tectonics' (BIFROST), the overall goal of this project is to study the effects of post-glacial rebound in Fennoscandia. It started in 1993 as an initiative of the Onsala Space Observatory (OSO) and the National Land Survey of Sweden (NLSS). Over the years it has evolved into an international collaborative project involving Sweden, Finland and several other Baltic countries, with support from the Smithsonian Astrophysical Observatory (SAO) and UNAVCO in the US. In contrast with other projects, the GPS network consists of a mix of permanent stations and non-permanent stations which are occupied during yearly campaigns. The permanent network was gradually expanded in the course of the project and now includes 20 sites in Sweden (SWEPOS network) and 12 sites in Finland (FINNET). In addition, about 55 stations, many of which are located near tide gauge sites in the various countries, are observed during the yearly campaigns.

4.3.9. *Pegel-Caucasus* (*PEKA*) *project*—This project, which is a combined effort of various institutes in the CIS, coordinated by the Institute for Applied Astronomy (IAA), and IfAG, focuses on the Northern Caucasus. The aim is to determine the extent and magnitude of the crustal motions along this section of the Eurasia/Arabia plate boundary. During two measurement campaigns, in July 1993 and September 1994, a dense network comprising 19 and 23 sites, respectively, was observed.

4.3.10. *CATS project*—Since 1992, GFZ-Potsdam, in close cooperation with numerous institutes in Russia and several Central Asian countries, has established a large GPS network in the Pamir-Tienshan region. This Central Asian Tectonic Science (CATS) project aims to study the mechanisms which were involved in the formation of this region. It is generally accepted that the Tienshan mountains were created as a result of the collision and subsequent penetration of the Indian plate into the Eurasian plate, although the region is located 1000–2000 km away from the collision zone. Therefore, this region offers an interesting opportunity to study the process of intracontinental shortening. The area of interest extends from 63–81° East longitude and from 37–46° North latitude. In August 1992, a network of 40 points was observed for the first time. This was repeated in August–September 1994, when the network was extended to 73 points of which 64 points were actually occupied, including 39 points of the 1992 network. In 1995, five more points have been added.

4.3.11. *Baikal project*—Russian and French scientists, from the Institute of the Earth's Crust in Irkutsk and the Laboratoire de Geodynamique in Paris, have collaborated since 1989 in a scientific project to study the Baikal rift zone. This is a geodynamically interesting region, because it may provide essential information for the understanding of the processes associated with the formation of continental margins. For this purpose, in August 1994, an initial GPS campaign was organized during which observations were collected at 11 sites distributed across the southern part of the Lake Baikal rift. In August 1995, one important baseline (two points) was remeasured and two new points were added in the central/northern part. A full reoccupation is planned in the near future.

4.3.12. *SELF project*—In response to the increased interest in the potential problems due to sea-level rise, the 'SEa Level Fluctuations: geophysical interpretation and environmental impact' (SELF) project was created. Its aim is to assess the factors causing sea-level rise in the Mediterranean and Black Sea regions. The project involves partners from six European countries and is coordinated by the University of Bologna. An important aspect is to provide accurate GPS links between well-established tide gauges and the global network of SLR and VLBI stations. The network consists of 28 stations which have been observed with GPS in 1993 and 1994. In 1995, the SELF-2 follow on project was approved, which includes a further expansion of the network.

4.3.13. *BSL project*—The Baltic Sea Level (BSL) project (Kakkuri *et al.*, 1994) is an international cooperation programme between the countries on the Baltic Sea, initiated by the IAG and coordinated by the Finnish Geodetic Institute (FGI). The main goal is unification of the vertical datums, with a view to monitor sea-level and observe post-glacial rebound in the sea area. During the first GPS campaign in 1990, measurements were carried out at 30 tide gauges and nine fiducial stations. This campaign was hampered by several problems, however, such as an incompatible mix of GPS receivers and unfavourable ionospheric conditions. The network was successfully remeasured and expanded to 35 tide gauges and 12 fiducial stations during the second campaign in 1993.

It is evident from all these projects that the Eurasia/Africa/Arabia plate boundary is pretty well covered with geodetic networks, although there are hardly any stations on the

African plate. Towards the west and the east, the coverage appears to be rather sparse. The actual situation may be a little bit better, however, because there may be other projects which are not included in the above compilation. It is known, for example, that measurements have been done in the past in Greenland and Iceland, but the status of these projects is currently unknown to the author.

In this summary, only campaign-like projects have been mentioned. However, in many countries permanent GPS arrays are being installed for various purposes, usually as reference stations in a navigation network. Good examples are the SATREF network in Norway and the SWEPOS network in Sweden, or the European component of the permanently operating IGS network. Obviously, the data from these networks are also very useful for scientific investigations.

Therefore, it seems that the eastern part of the Eurasian plate needs the most expansion in coverage. It is hoped that this may be achieved through intensified international cooperation with the countries of the CIS.

5. WEGNET: A GPS REFERENCE NETWORK FOR WEGENER

As has been shown, the practice of high precision GPS geodesy has evolved in recent years. In the 1980s, investigators carried out independent regional campaigns, sometimes temporarily installing receivers at a few VLBI or SLR control points (fiducial stations) to improve orbit determination and reference frame definition. The new mode of operation is exemplified by the IGS as described elsewhere in this paper. As a result, today's investigator can position a single receiver in the IERS terrestrial reference frame (ITRF) with centimeter-level accuracy, and with a regional network can derive relative positions with an accuracy of a few millimetres.

5.1. *The need for a regional reference network*

At the few-millimetre level, many geophysical signals and systematic effects cover a broad spatial and temporal range. For example, the loading of the Earth's crust due to changing atmospheric pressure typically causes variations in station height of 3 cm peak-to-peak above 45° latitude. Crustal loading from ocean tides can cause height variations of similar amplitude. For both horizontal and vertical motion, it is also important to have sufficient regional reference frame control (as well as global) in order to interpret anomalous velocity estimates, which might be due either to local effects, or a regional disagreement with a priori models. It is important to distinguish the latter from the former, especially since the latter may lead to revision of physical models of that particular region. If a sufficiently dense regional reference network were not available, local instability might be misinterpreted as a regional phenomenon. Interpretation of results in this high-accuracy regime (i.e. at the few millimetres level) requires a permanent network of GPS stations in the region of interest, which is routinely analysed together with a sufficient number of IGS stations such that geocentric positions can be monitored.

5.2. *Complementary aspects of IGS and WEGENER*

As the current WEGENER program is defined, the region of interest can be roughly characterised as extending east–west from Greenland to mid-Asia in the northern hemisphere. There are currently about two dozen IGS stations in this region, and almost all are in Europe. For the purposes of WEGENER, it is recommended that a dense network of permanently operating GPS stations be installed to complement the existing IGS network, especially in those areas that are currently sparsely monitored. This proposal tracks well with the plans for further densification of IGS.

However, the goals of IGS and WEGENER are different, so it cannot be expected that IGS will organise the development of a reference network that meets all of WEGENER's needs. Whereas IGS is ultimately concerned with providing a relatively evenly distributed global reference network of perhaps 60 'core' stations for optimal determination of GPS orbits and polar motion parameters, WEGENER investigators are primarily interested in geodynamical signals which are not uniformly distributed either spatially or temporally. These different needs indicate that, despite the fact that IGS-derived orbits are sure to meet the accuracy requirements of WEGENER investigators, the IGS network itself will require densification in those areas of geodynamical interest so that signals may be unambiguously interpreted.

As for data analysis, IGS already has a mechanism in its 'Terms of Reference' by which WEGENER groups can officially participate. Groups can be inducted as 'IGS Associate Analysis Centres' (AAC). AACs can perform such tasks as the routine analysis of regional networks, or the unification of various group's solutions into a dense, consistent, global solution. The actual scheme for achieving this (including analysis standards, etc.) is currently being developed by IGS. Therefore, there is a synergy between IGS and WEGENER: IGS provides a global infrastructure, precise orbits and global solutions; WEGENER provides a regional infrastructure and precise regional solutions.

5.3. *Guidelines for WEGNET installation*

We recommend that densification proceeds according to the following guidelines:

1. For purposes of compatibility, homogeneity, and simplicity, we recommend that WEGNET build on the existing IGS system according to IGS standards as they relate to building construction, equipment, communications, data formatting and handling, and data analysis. IGS has detailed documents on standards, especially with regard to station installation (building construction and equipment). The standard data exchange format is RINEX 2.
2. Densify the current IGS network until the distance from any location in the entire WEGENER region is a minimum of 1000 km from the nearest permanent station.
3. Provide further densification in those areas of special WEGENER interest according to the needs to resolve ambiguous interpretation. For example, a program of permanent network densification to characterise current day post-glacial rebound is in progress in Fennoscandia. Typical nearest-station distances are 250 km. However, for a more complete picture of post-glacial rebound in northern Europe, there is a need to extend this densification to include a few stations in the British Isles, which currently has only a single IGS station. As another example, permanent stations should be considered at selected tide-gauge benchmarks as part of the effort to distinguish changes in sea-level from vertical motions of the land.
4. In parallel with the network densification, build on the current IGS infrastructure so that data retrieval, storage, and analysis be carried out in a consistent manner. This is extremely important, since it is likely that the number of permanent stations will be too many for any single analysis group to deal with, and it is crucial that solutions derived at different analysis centres can be brought together into one consistent, comprehensive solution.

Table 4. Server–client relationships between WEGENER, IGS and IERS

Server	Client	Products
IGS	IERS	Global solutions, new models, quality assessment
IERS	IGS	UTPM/ITRF, standard models, quality assessment
WEGENER	IGS	Raw data, regional solutions, quality assessment
IGS	WEGENER	Raw data, precise orbits, global solutions, analysis standards, infrastructure, quality assessment
WEGENER	IERS	Regional solutions, new models, quality assessment
IERS	WEGENER	UTPM/ITRF, standard models, quality assessment

UTPM, Universal Time and Polar Motion.

5.4. *Areas of cooperation*: *WEGENER, IGS, and IERS*

Table 4 summarizes the server–client relationships between WEGENER, IGS, and IERS, and a few key topics will be expanded below.

5.4.1. *Reference frames*—IGS is already formally cooperating with IERS, and is making significant contributions to maintaining the terrestrial reference frame (ITRF) and polar motion series. WEGENER should also cooperate with these two agencies in contributing to ITRF. In return, WEGENER can be better assured of the consistency of station coordinates with the frame defined by the precise IGS orbit ephemerides.

5.4.2. *Data exchange*—IGS makes data from permanent sites freely available for research purposes via the Internet from three data centres (IGN in Paris, CDDIS in Washington DC, and SIO in California). WEGENER should in the same spirit of cooperation make data similarly available. WEGENER should explore the possibility of utilizing existing IGS resources, but where the burden is too great, should offer to expand the IGS system in a consistent way.

5.4.3. *Solution formats*—Although RINEX 2 is the standard data exchange format, there is currently no accepted standard format for the exchange of solutions. IGS and WEGENER should work together to produce such a format, and on the means to combine solutions from various analysis groups in a consistent way. One practical way to achieve this is to involve those who work in both organizations to coordinate this effort.

5.4.4. *Product quality assessment*—WEGENER is potentially IGS's largest customer, and as such, is in a good position to provide feedback on the quality of IGS products. For example, a regional network operated as part of the WEGENER project could routinely provide IGS with statistics that indicate product quality, such as a fit to baseline repeatability as a function of distance, and statistics to indicate which days may be problematic. IGS might then use this information to debug problems, leading to more reliable, accurate products.

5.4.5. *Standard models and analysis*—IERS provides standard models, but it is the analysis groups such as those in IGS and WEGENER which provide new information to revise the standards. For example, IGS might be in a natural position to give advice on orbit modeling standards, and WEGNER might be in a natural position to give advice on Earth models which define the standard reference frame (e.g. post-glacial rebound and current day loading effects).

6. SOLICITATION FOR PARTICIPATION

During a WEGENER meeting Potsdam, on October 27 to 29, 1993, an ad-hoc working group was established, which generated the first ideas about the outline of the network. The selection of sites was governed by the following guidelines:

- available infrastructure
- collocation with other techniques (SLR/VLBI, tide gauge, etc.)
- approximately 1000 km grid
- integration with existing or planned local networks
- sites on different tectonic plates, etc.

This led to a preliminary list of sites, which has been under continuous review since the meeting. Here, the current (September 1995) version of the list is presented in Table 5, and a map of the proposed sites is shown in Fig. 7. It is emphasized that many of the sites still have to be established and some of them are nothing more than dots on the map, in locations where it would be favourable to have a station. This holds in particular for the sites in the Eastern part of Eurasia and in Africa. Also, the cooperation of many institutions operating the receivers at the proposed sites has not yet been confirmed. However, the list is representative of the kind of network that is envisaged.

Therefore, it is proposed that WEGENER should be soliciting proposals for the installation and operation of GPS station facilities, including site selection, building construction, hardware installation, and communications capability. Proposers will be referred to the IGS Central Bureau for standards regarding station installation. Also, proposals for the routine analysis of the data from regional sub-networks of WEGNET should be solicited. The IERS Standards document will serve as a basis for the analyses and potential proposers are invited to work with IGS to refine those standards for this specific activity. Analysis groups are encouraged to pursue membership in IGS as Associate Analysis Centres. In addition to producing solutions for their own scientific investigations, these groups must agree to submit and make available routine solutions produced in accordance with IGS/WEGENER standards for the purpose of combination with other solutions. This would mean agreement to adopt exchange formats when they become standardised. As a point of information, it is likely that IGS will only be interested in a subset of regional stations, whereas WEGENER will be interested in all approved stations.

7. CONCLUSION

The rationale and guidelines for implementing an operational WEGENER GPS network, called WEGNET, which would build upon the existing IGS infrastructure, have been outlined. Also, the possible working relationships between WEGENER, IGS, and IERS, have been explored, while is was pointed out where collaboration is desirable for everyone's benefit. In particular, WEGENER groups who intend to routinely process permanent regional GPS networks are encouraged to apply to become IGS Associate Analysis Centres. It is recommended to follow up this proposal with a call for participation for station implementation and routine analysis.

8. SUMMARY

In this paper, information about GPS has been summarised which may be relevant for the WEGENER project. It is clear that GPS is a powerful technique which is indispensable

Table 5. Preliminary list of proposed WEGNET sites

Abbreviation	Full name	Country	Longitude	Latitude	Status	Agency	Collocation	
							VLBI	SLR
TROM	Tromso	Norway	18.9	69.6	Existing	SK	X	X
NYAL	Ny-Alesund	Norway	11.8	78.9	Existing	SK	—	—
ONSA	Onsala	Sweden	11.9	57.3	Existing	OSO	X	
METS	Metsahovi	Finland	24.3	60.2	Existing	FGI	X	X
GRAZ	Graz	Austria	15.4	47.0	Existing	ISRO	—	X
MATE	Matera	Italy	16.7	40.6	Existing	ISA	X	X
HERS	Herstmonceux	United Kingdom	0.3	50.8	Existing	RGO		X
MADR	Madrid	Spain	−4.2	40.4	Existing	NASA/JPL	X	—
KOOT	Kootwijk	Netherlands	5.8	52.1	Existing	DUT	—	X
ZIMM	Zimmerwald	Switzerland	7.4	46.8	Existing	BfL	—	X
WETT	Wettzell	Germany	12.8	49.1	Existing	IfAG	X	—
USUD	Usuda	Japan	138.3	36.1	Existing	ISAS	X	
TAIP	Taipei	Taiwan	121.5	25.0	Existing	IESAS	—	—
MASP	Maspalomas	Canary Islands, Spain	−15.6	27.7	Existing	ESOC	—	—
STJO	St. Johns	Canada	−52.6	47.5	Existing	EMR	—	—
KITA	Kitab	Uzbekistan	66.5	39.0	Existing	GFZ		—
JOZE	Jozewslaw	Poland	21.5	51.0	Existing	WUT	—	
WUHA	Wuhan	China	114.3	30.5	Planned	WTU/NGS	—	X
SHAN	Shanghai	China	121.1	31.0	Planned	SAO/NASA/JPL	X	X
CHAN	Changchun	China	125.4	43.7	Planned	SAO	—	X
HOFN	Hof	Iceland	−15.1	64.2	Planned	SK	X	—
BEIJ	Beijing	China	116.2	39.5	Planned	NBSM/GFZ	—	
URUM	Urumchi	China	87.3	43.4	Planned	GFZ	—	
ULAN	Ulan Bator	Mongolia	106.5	47.5	Planned	GFZ	—	—
BADA	Badari	Russia	102.1	51.7	Planned	IAAS/JPL	—	—
NOVO	Novosibirsk	Russia	83.0	55.0	Planned	GFZ	—	—
ANKA	Ankara	Turkey	32.5	39.5	Planned	IfAG	—	—

USSU	Ussuriysk	Russia	131.5	43.4	Planned	SDC/JPL	—	—
RIYA	Riyadh	Saudi Arabia	46.4	24.3	Planned	?	—	—
SFER	San Fernando	Spain	−6.1	36.2	Planned	?	—	
NORI	Norilsk	Russia	88.0	69.1	Planned	?	—	—
PETR	Petropavlovsk-Kamchatski	Russia	158.4	53.0	Planned	GFZ	—	—
CARN	Carnoustie	United Kingdom	−2.7	56.4	Existing[a]		X	—
BARG	Bar Giyyora	Israel	35.0	31.7	Existing[a]		—	X
MIZU	Mizusawa	Japan	141.2	39.1	Existing[a]		X	—
MIYA	Miyazaki	Japan	131.4	32.0	Existing[a]		X	—
SHIN	Shintotsugawa	Japan	141.8	43.5	Existing[a]		X	—
CHIC	Chichijima	Japan	142.1	27.0	Existing[a]		X	X
MINA	Minami Tori Sima	Japan	153.9	24.2	Existing[a]		X	X
BRES	Brest	France	−4.5	48.4	Existing[a]		X	—
HELW	Helwan	China	31.3	29.8	Existing[a]		—	X
SAOM	San Miguel	Azores, Portugal	−25.6	37.7	Existing[a]		X	—
RIGA	Riga	Latvia	24.0	56.9	Existing[a]		—	X
SIME	Simeis-Katzively	Ukraine	33.9	44.4	Existing[a]		—	X
DION	Dionysos	Greece	23.9	38.0	Existing[a]		—	X
NOTO	Noto	Italy	14.9	36.8	Existing[a]		X	X
CAGL	Cagliari	Italy	8.9	39.1	Existing[a]		—	X
DJIB	Djibouti	Djibouti	43.1	11.3	Possible			—
THUL	Thule	Greenland	−69.0	76.3	Possible		—	—
IVIG	Ivigtut	Greenland	−48.0	61.1	Possible		—	—
SCOR	Scoresbysund	Greenland	−22.0	70.3	Possible		—	—
LIME	Limerick	Ireland	−8.3	52.4	Possible		—	—
FES	Fes	Morocco	−5.0	34.0	Possible		—	—
TRIP	Tripoli	Libya	13.1	32.5	Possible		—	—

[a] Non GPS.

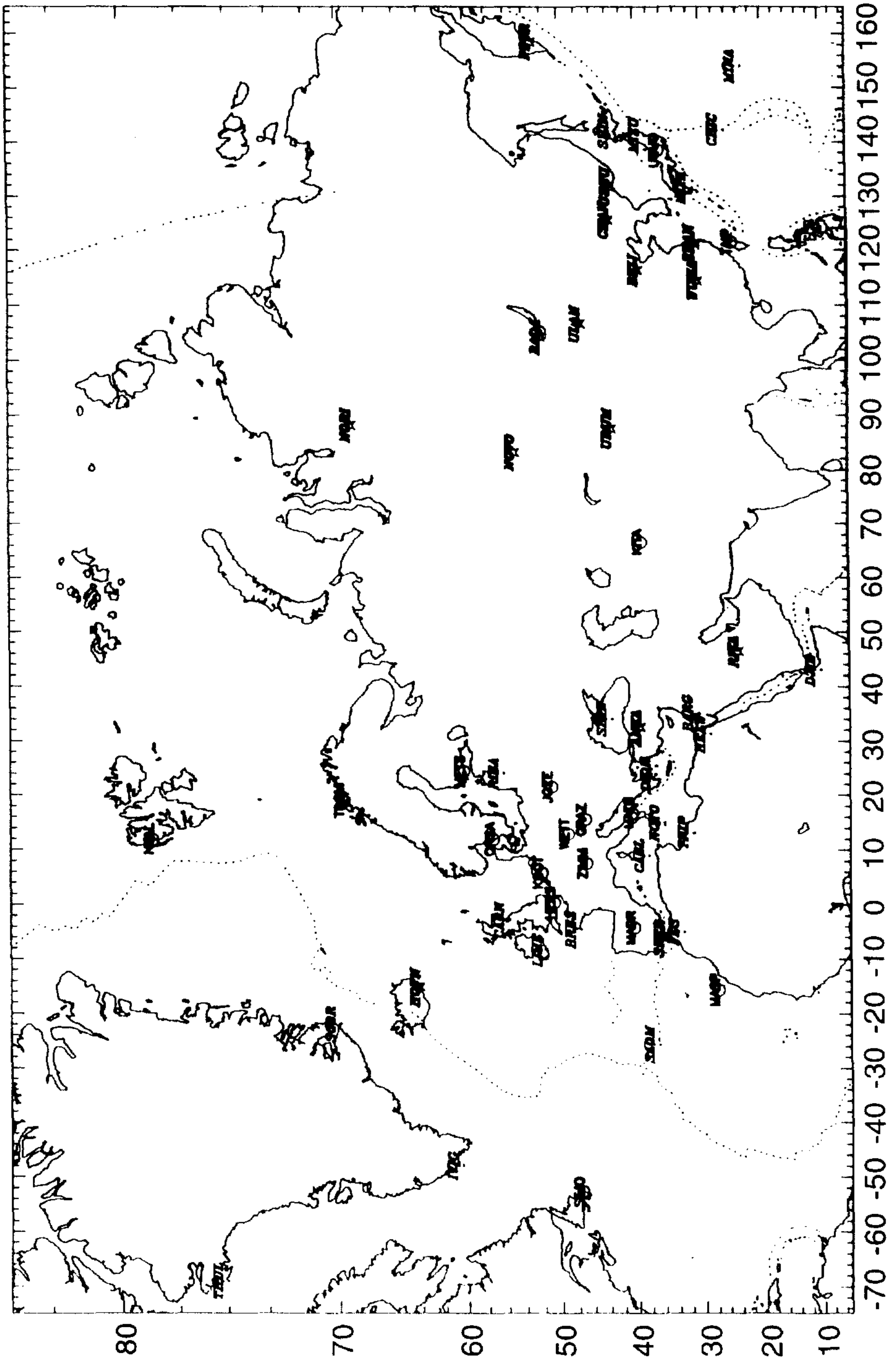

Fig. 7. Preliminary map of the proposed WEGNET network.

to achieve the scientific goals of WEGENER. Within the general area of interest of WEGENER, numerous independent regional GPS measurement projects have been and continue to be carried out. It is felt that the overall scientific yield of these projects can be further enhanced if WEGENER could provide the infrastructure to connect all the relatively small networks of these projects. Therefore, the establishment of a dedicated permanent WEGENER GPS Network (WEGNET) is proposed, which may also serve as a regional densification of IGS.

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