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ASSOCIATE ANALYSIS CENTERS

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RAPID SERVICE AND PREDICTION

U.S. Naval Observatory:
Center for Rapid Service and Predictions

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Introduction

The mission of the U.S. Naval Observatory (USNO) includes determining the positions and motions of celestial bodies, measuring the Earth's rotation and orientation, maintaining the master clock for the U.S, and disseminating precise time. The Earth Orientation (EO) Department contributes to this mission by collecting suitable observations and performing data analyses to determine and predict the time-varying orientation of the terrestrial reference frame within the celestial reference frame. The key parameters determined and disseminated are polar motion coordinates, universal time (UT1), precession, and nutation. The user community is very broadly based with the primary applications being high-accuracy navigation and positioning, particularly for real-time uses.

In order to accomplish these objectives, USNO collaborates closely with a large number of other groups and organizations, and uses a combination of results from a variety of techniques. Very long baseline interferometry (VLBI) is essential in order to maintain accurate knowledge of UT1, the celestial pole, and the celestial reference frame, which is realized by the positions of about 600 extragalactic radio sources. GPS is vitally important also, for its high accuracy, continuous data, and rapid product availability. This report summarizes the current status of USNO participation with the IGS and GPS during 1998.

IERS Sub-Bureau for Rapid Service and Predictions

The IERS Sub-bureau for Rapid Service and Predictions of Earth orientation parameters (EOPs) is hosted by the EO Dept. at USNO. EOP results contributed by many analysis centers derived from observations by VLBI, satellite laser ranging to LAGEOS, lunar laser ranging, or GPS are combined into a homogeneous daily time series which is updated and distributed twice each week as *IERS Bulletin A*. Combined EOP values for the recent past are published together with predictions extending a year into the future. The "final" EOP values are published monthly in *IERS Bulletin B*, which is prepared by the IERS Central Bureau based at the Observatoire de Paris. The major changes affecting *IERS Bulletin A* during 1998 are summarized in Table 1.

In recent years, the *Bulletin A* polar motion results have been dominated by the precise, daily determinations of the IGS combined Final products, with the Rapid series being used for the most recent measurements. The Rapid determinations are quite important for *Bulletin A* by providing timely (delivered within 22 hours after each UTC midnight, which shortened to 17 hours starting 29 November 1998), high-quality results which are most significant for the polar motion predictions needed by real-time users. Implementation on 01 March 1998 of the much more robust and improved terrestrial reference frame realization proposed by Kouba *et al.* (1998), where the coordinates and velocities of 47 sites are constrained to their ITRF96 values, has produced significantly more stable polar motion results (Mireault *et al.*, 1999). This, in turn, has improved the quality and reliability of near-term *Bulletin A* polar motion predictions.

Table 1. *IERS Bulletin A* changes during 1998.

01 March	IGS changed from 13 ITRF94 to 47 ITRF96 sites for fiducial reference frame
03 March	near-term polar motion prediction algorithm improved (Ray and Luzum, 1998)
27 April	most recent 15 days of EMR's UT added
May-September	refinements in calibration, weighting, and assimilation of GPS-based UT series
11 June	daily, automated updates of *Bulletin A* EOP files became available publicly
20 October	improved GPS-based UT series from Kammeyer (USNO) introduced
29 November	daily EOP updates shifted from ~22:10 to ~17:10 UTC
29 December	span of assimilated GPS-based UT series extended from 15 to 22 most recent days

IERS Bulletin A has also become increasingly reliant on IGS estimates of length of day (LOD) and UT1-like variations. The IGS combined LOD results are used in the *Bulletin A* combination to extend the UT1 value of the most recent VLBI determination forward by integration. In addition, independent sets of GPS-based estimates of univeral time, derived at USNO and the EMR Analysis Center (Natural Resources Canada), are also included in *Bulletin A*. About two weeks of the most recent estimates are used (extended to about three weeks in December 1998), after calibration in offset and rate compared to overlapping UT1 results from VLBI. These three series together have proven very successful in extending UT1 results forward from the latest VLBI determinations, which can have a latency of up to about a week. As a consequence, the last non-predicted UT1 value in *Bulletin A* is now generally more accurate than 100 μs, usually considerably more so.

Errors in predicted EOP values are a significant source of systematic error in the IGS Predicted orbits. An EOP error of 1 mas corresponds to a net rotation of the GPS constellation of up to ~13 cm at altitude. Martín Mur *et al.* (1998) have stressed the need for improved EOP predictions for use in computing the IGS Predicted orbits. Partly to address this concern, refinements already under development were implemented in *Bulletin A* on 03 March 1998 (Ray and Luzum, 1998). The improvement is most significant for the shortest prediction intervals (53% for 1 day) with diminishing effect over longer spans. We estimate that during 1998 the actual *Bulletin A* prediction errors for 1.5 day after the most recent data, appropriate for the IGS Predicted orbits, were about 0.75 mas for each component of polar motion and about 2.4 mas for UT1 (or 0.16 ms).

For real-time users, given two updates of *Bulletin A* each week, the longest prediction interval was ~7 days. Because EOP prediction errors increase steadily with time since the most recent observations, daily updating of the *Bulletin A* data files was implemented in mid-1998. This process has reduced the lag since the most recent data from ~7 days at the start of 1998 to ~41 hours at the end of the year, with a corresponding improvement in EOP prediction accuracy for real-time users.

As part of its contribution to the IGS, USNO prepares regular reports and plots of the performance of each IGS Analysis Center compared with *Bulletin A*, which are available at <http://maia.usno.navy.mil/>. All EOP data files are available by anonymous ftp from the same site.

IGS Rapid Service Associate Analysis Center

During 1998, USNO continued its participation as a contributor to the IGS Rapid products. Submissions were successfully made for 328 of the 365 days (89.9%). The average weighted RMS of the USNO orbit residuals for the year was 12.7 cm, with a median of about 10 cm. Ignoring 10 days in late January-early February, when the IGS data network was severely handicapped by an outage at JPL, the average WRMS orbit residual for USNO was 11.3 cm. Steps were taken to refine the GPS orbit modelling strategy, most of which were not completed until early 1999. A two-stage process was implemented with a first solution using 30 sites followed by a second solution using 33 sites. The results of the first solution are used to adjust satellite-dependent data weights and stochastic acceleration sigmas for the orbit parameterizations in the second solution. In this way, the sometimes erratic behavior of certain satellites can be accommodated better in the solutions submitted to the IGS. Strengthening checks of data quality and site/satellite rejection has been an ongoing process necessitated by the continuous emergence of new types of data problems and configuration changes at the stations. Significant changes in the USNO Rapid analysis strategy during 1998 are summarized in Table 2.

Table 2. USNO Analysis changes during 1998.

01 March	IGS change from 13 ITRF94 to 47 ITRF96 sites for terrestrial reference frame
26 March	reference clock changed from ALGO to USNO
01 May	Hatanaka data compression fully implemented
12 July	version 2 ERP file format implemented
03 September	operations moved from HP 735 to HP J2240 workstation
03 September	2-step solutions started using 33 sites for 2nd run
03 September	IERS sub-daily EOP model implemented
29 September	deweighting of poorly fit satellites implemented
29 November	IGS adopts values for satellite antenna offsets (USNO implementation delayed till January 1999)
29 November	IGS Rapid submission deadline shifted from 21:00 to 16:00 UTC
16 December	IGS combination center moved to AIUB/Berne

The data analysis software used at USNO continues to be the GIPSY/OASIS II package, version 4.8, developed and maintained by JPL.

V. Slabinski joined our staff in late 1998 with the task to develop an operational GPS orbit prediction capability. Routine submissions for the IGS Predicted orbits began in mid-1999.

GPS Time Transfer Activities

A growing interest at USNO is the use of geodetic GPS techniques for precise time transfer. Besides full participation in the IGS/BIPM timing project (Ray, 1999), USNO supports this effort in a variety of other ways. In addition to the AOA TurboRogue SNR12 receiver previously installed in Washington, DC connected to the USNO Master Clock (MC) as its frequency reference, a second receiver was deployed at Schriever Air Force Base in Colorado Springs on 25 March 1998. This is the site of the USNO Alternate Master Clock (AMC) and the operations center for GPS. The MC and AMC are kept closely synchronized by hourly two-way satellite time transfer (TWSTT) observations. These IGS sites therefore serve as important comparison sites in the IGS/BIPM project. On 12 August 1998, the USNO receiver was moved to an environmentally controlled chamber within the clock vault and the antenna cable was replaced with a new type having a much lower sensitivity to temperature changes. These changes were highly effective, reducing diurnal variations to the noise level. In addition, the Swiss groups at AIUB and OFMET deployed one of their geodetic time transfer terminals (Overney *et al.*, 1998) at USNO, beginning in July 1998, for further comparisons.

USNO began posting plots of clock analysis results from the Rapid solutions beginning 19 July 1998. In addition, a second set of "Final" clock solutions began on 06 September 1998 using a larger network consisting of many sites equipped with high-quality frequency standards; these solutions use the IGS Final orbits and EOP values without adjustment. Plots and data files are distributed for the Final clock solutions. All of these results, as well as further information, are available at the Web site <http://maia.usno.navy.mil/gpsclocks/index.html>.

GPS Determinations Of Universal Time

As before, Kammeyer's (1999) operational procedures continue to determine UT1-like variations by comparing observed, Earth-fixed GPS ephemerides to numerically propagated models of their orbit planes. The modeled orbit planes are propagated using empirical models for the orbit-normal component of the radiation pressure acceleration. These models are expressed in terms of the angle from the orbital angular momentum to the Sun direction and the angle from the projection of the Sun direction onto the orbit plane to the position vector of the satellite. For each satellite and each time, there is a unique axial rotation angle which brings the observed Earth-fixed positions into alignment with the propagated orbit plane. The difference between the ascending node of the modeled orbit plane and the actual orbit plane for each satellite causes this rotation angle to differ by an offset from Greenwich apparent sidereal time. Adding to the rotation angle an estimate of this offset gives a single-satellite estimate of sidereal time, and equivalently, UT. Taking the median of these estimates for the 12 satellites modeled gives the UT estimate reported to *IERS Bulletin A*.

In October 1998, Kammeyer made significant changes in his operational procedures, including the source of the observed orbits, the models used in propagating orbit planes, and the method of estimating node offsets. Rather than use the GPS orbits determined at USNO, the combined IGS Rapid orbits are now used. This ensures more reliable operation and better performance. The models of the orbit-normal component of the radiation pressure acceleration are now based on all changes in the orbit planes observed during 1996 and 1997, rather than the previous 1994-1995 period. Further, the method of estimating the node offsets, and thus the entire method of estimating UT, no longer uses any external information on UT apart from initial values.

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GLOBAL NETWORK ASSOCIATE ANALYSIS CENTERS

GNAAC Coordinate Comparisons at JPL for GPS Weeks 813-1016

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Global Network Associate Analysis Center (GNAAC) activities began at JPL starting with GPS week 813 (95Aug06). Constraint removal was implemented on week 821 (95Oct01) and a fully rigorous combination was computed starting with week 837 (96Jan21). Sinex 1.0 format was implemented on week 890 (97Jan26). Starting with week 1016 (99Jun27) the Sinex format has been upgraded to use more information from the igs.snx file at the igscb and sites which do not have a log file at the igscb are excluded from the combination.

Solutions submitted from COD, EMR, ESA, GFZ, JPL, NGS, and SIO are obtained from the CDDIS each week. If necessary, apriori constraints are removed to the level of about 10 m. Small but finite internal constraints are applied to the linear combinations of estimates which correspond to the 7 reference frame parameters. This leaves the estimates for each solution competely unchanged but reduces the sigmas so that they reflect internal errors only. Each pair of solutions is then compared by estimating a 7-parameter Helmert transformation to minimize the least-squares coordinate residuals. All common sites are used. The errors from each solution are scaled to make CHI^2/DOF roughly equal to one for all pairs and four sigma outliers are removed. The transformation parameters for each pair are given in the report along with the WRMS of residuals. Tables 1 and 2 summarize the transformation parameters with respect to JPL for all weeks and the most recent 52 weeks, respectively.

A free-network combination of solutions from all centers is also computed. The combination is computed using the full covariance information from each center and then submitted to the CDDIS along with the summary report. Sites common to all solutions are used to compare each solution with the combination. The comparison is carried out by application of internal constraints and estimation of a 7-parameter Helmert transformation. The WRMS residuals are tabulated in the report. Tables 3 and 4 summarize the WRMS residuals for each center for all weeks and for the most recent 52 weeks.

Table 1. Mean Geocenter and Scale with Respect to JPL for GPS Weeks 837-1016.

Center	TX	TY	TZ	Scale
	cm	cm	cm	ppb
COD	0.7	-0.2	0.4	0.6
EMR	0.2	-9.4	9.6	-0.1
ESA	0.2	1.2	2.4	1.2
GFZ	-0.3	-4.2	1.7	-0.1
NGS	0.0	-14.1	9.3	-1.3
SIO	-0.3	-0.3	8.5	-0.5

Table 2. Mean Geocenter and Scale with Respect to JPL for GPS Weeks 965-1016.

Center	TX	TY	TZ	Scale
	cm	cm	cm	ppb
COD	0.4	-0.1	0.7	0.7
EMR	-0.2	-4.6	13.6	-0.4
ESA	-0.3	0.2	1.7	-0.3
GFZ	0.0	-0.1	-0.1	-0.9
NGS	-1.0	-1.9	9.1	-0.4
SIO	-0.8	-0.7	13.5	-0.6

Comparisons over the last 52 weeks show geocenter agreement of better than 1 cm in all components for COD, GFZ, and JPL. Improvements in geocenter estimates were observed at both GFZ and NGS. The scale agreement over this same period is better than 1 ppb for all centers. Weekly coordinate comparisons agree at the level of roughly 2 mm N, 2 mm E, and 5-7 mm V for COD, GFZ, and JPL over the last year. Significant improvements in coordinate agreement were observed at GFZ and NGS.

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Table 3. Mean Coordinate WRMS for GPS Weeks 837-1016.

Center	North mm	East mm	Vertical mm
COD	2.3	2.7	8.1
EMR	5.2	8.7	11.6
ESA	4.3	7.4	20.1
GFZ	2.6	5.6	9.5
JPL	2.0	2.3	6.8
NGS	8.9	12.7	12.5
SIO	3.0	4.0	8.7

Table 4. Mean Coordinate WRMS for GPS Weeks 965-1016.

Center	North mm	East mm	Vertical mm
COD	1.8	2.2	7.3
EMR	5.2	8.1	11.4
ESA	4.8	7.6	12.1
GFZ	1.8	1.8	5.5
JPL	2.2	2.0	5.3
NGS	5.1	7.3	9.0
SIO	3.7	3.8	9.5

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Annual Report 1998 of RNAAC SIRGAS

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Introduction

The IGS Regional Network Associate Analysis Center SIRGAS (RNAAC SIR) continued the weekly processing of all the available data of permanently observing GPS stations in the mainland of South America and the surrounding areas. The weekly station coordinate solutions contribute to the combined polyhedron solutions of the Global Network Associate Analysis Centers (GNAAC).

Station Network

In 1998, the station configuration of the RNAAC SIRGAS has been extended by including six new IGS stations (Aguas Calientes, Mexico; Palmer and Vesleskarvet, both Antarctica; Gough, South Atlantic; Riobamba, Ecuador; and Rio Grande, Argentina) and two additional stations in Argentina (Buenos Aires and Bahia Blanca), which are processed by the RNAAC only. The actual station network is shown in Figure 2. As we may see from Figure 1, there were some gaps in the continuous data delivery of several stations.

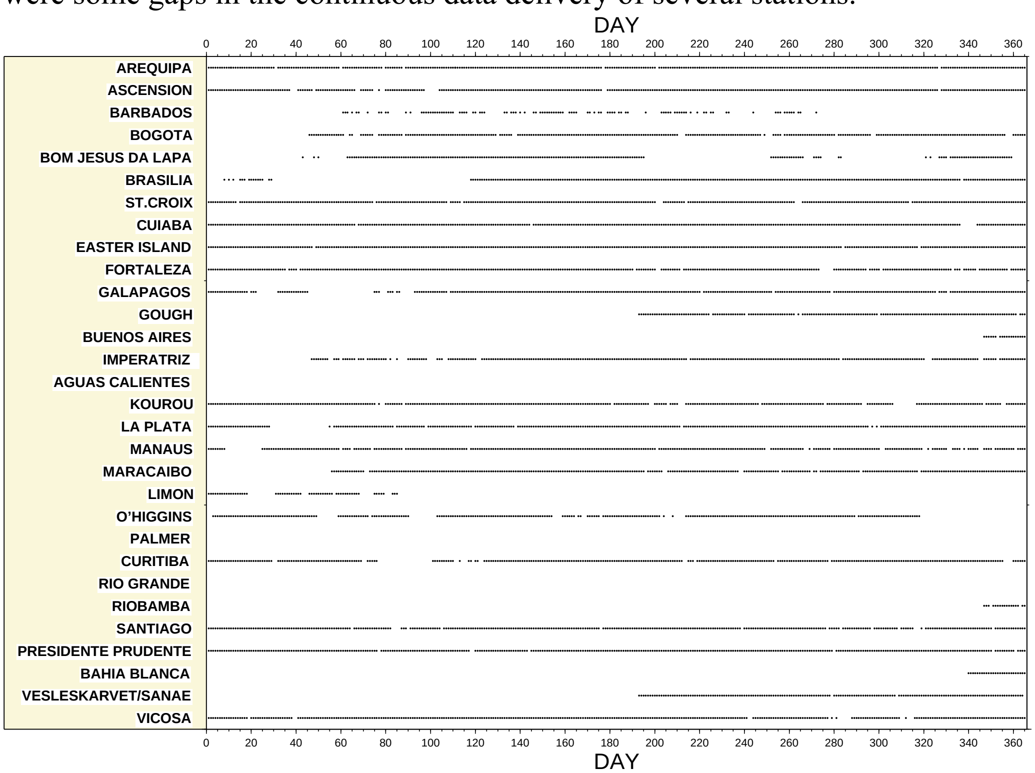

Figure. 1: Summary of Available RINEX Files in 1998

The stations Gough, Vesletkarvet, Riobamba, and Rio Grande started their observations already earlier than they were included in the RNAAC processing, Bahia Blanca, Buenos Aires and Aguas Calientes were processed since the beginning of their observations in 1998 and 1999, respectively.

The time series of the RNAAC SIRGAS stations are now long enough to derive station velocities. Figure 2 shows these velocities for stations with more than one year of observations derived from the weekly polyhedron of the GNAAC at MIT in comparison with the ITRF97 velocities.

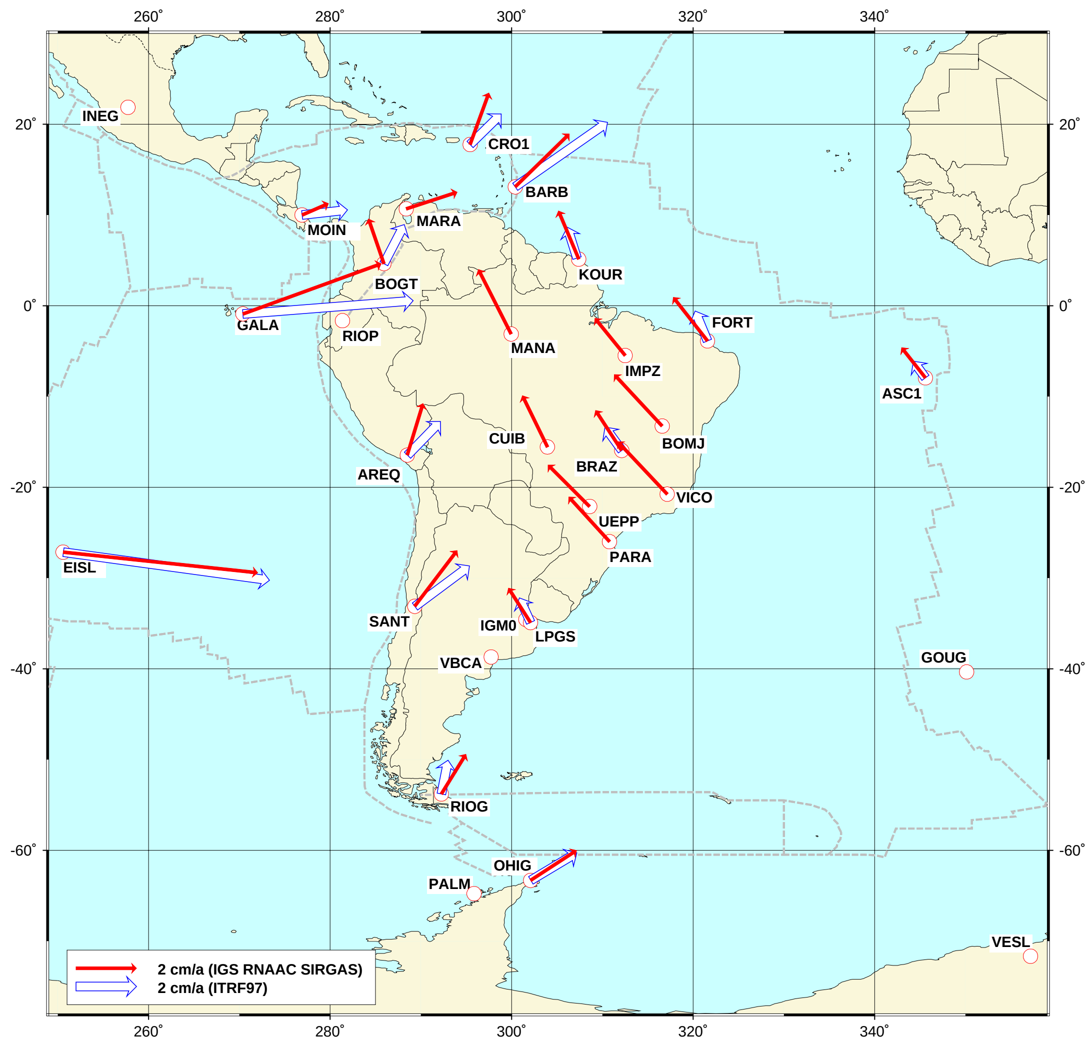

Figure 2: Comparison of IGS RNAAC SIRGAS and ITRF97 Station Velocities

In general, the velocities of both solutions fit quite well together. The velocities of the RNAAC SIRGAS stations in the eastern part of South America are in general greater, and in the western part of the continent less than the ITRF97 velocities. Nearly all the velocity vectors are directing more to the North in the RNAAC solution than in the ITRF97. One has to consider, however, the relatively short observation time.

AUSLIG RNAAC – 1998 Annual Report

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Introduction

AUSLIG continued processing all sites in the Australian Regional GPS Network (ARGN) during 1998. The weekly combined SINEX result files were submitted to the Crustal Dynamics Data Information System (CDDIS) as AUSLIG's role as an IGS type 2 Associate Analysis Centre.

Station Network

The station network processed by the AUSLIG RNAAC is shown in Figure 1. Twelve of the sixteen stations in this network are operated by AUSLIG. DST1, PERT TID2 and YAR1 are owned and operated by non-Australian agencies. A new AUSLIG site STR1 located at the new Mount Stromlo Satellite Laser Ranging observatory near Canberra is proposed to be added to the network during 1999.

The data from site TIDB was replaced by the data from site TID2 for all solutions from GPS week 967 onwards.

Data Analysis and Results

The Bernese GPS Software version 4.0 (Rothacher and Mervart 1996) is used for the GPS data processing. Daily solutions are computed using the following strategy:

- L3 double differenced phase observable.
- No resolution of integer ambiguities.
- Elevation cut-off angle of 20°.
- Estimation of tropospheric zenith delay parameters at 2 hourly intervals.
- IGS antenna phase centre variation model applied.
- IGS final orbits and EOPs held fixed.
- Site coordinates for a single site constrained (either TID2 or YAR1).

Seven daily solutions are combined at the normal equation level to obtain the weekly solution output in SINEX format submitted to the CDDIS. These solutions were tightly constrained to the ITRF coordinates at selected sites. Solutions up to and including GPS week 946 are in the ITRF94 system and were constrained to TID2 and YAR1. Solutions from and including GPS week 947 are in the ITRF96 system and were constrained to DAV1, HOB2, MAC1, PERT, TID2 and YAR1, selected from the 47 ITRF96 IGS reference sites.

The AUSLIG RNAAC weekly SINEX solution files were included in the Type 2 RNAAC combination generated by the Massachusetts Institute of Technology (MIT).

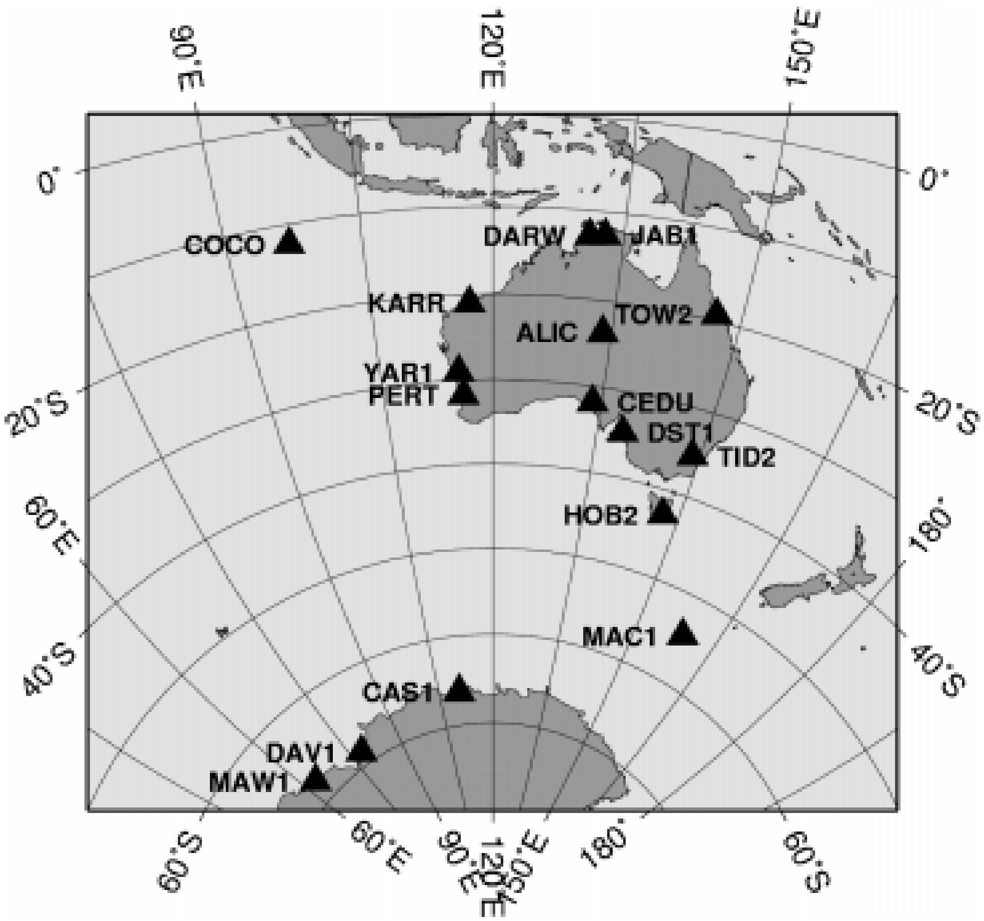

Figure 1. AUSLIG RNAAC station network as of 31 December 1998

References

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