PRARE System Performance

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Abstract

The two-way microwave satellite tracking system PRARE is in continuous operation onboard ERS-2 since May 1, 1995. With the assistance of a global network of mobile, autonomous PRARE ground stations, the PRARE space segment produces nearly permanently two-way pn-coded range and carrier shifted doppler measurements at sub-dm resp. sub-mm/s level of accuracy. These data are used by a number of international user groups to derive higher-level geodynamic products such as ERS-2 orbits, ground station coordinate solutions, Earth gravity field parameters, or ionospheric quantities.

The paper describes the up-to-date status and performances of the PRARE space segment, the PRARE ground tracking network and the PRARE control segment consisting of the Master Station in Oberpfaffenhofen, the Monitoring and System Command Station in Stuttgart and the Calibration Station in Potsdam. Additionally, some of the important data flow and preprocessing procedures as well as relevant data quantity, quality, validation, and distribution routines are summarized. Finally, some results of external calibration campaigns PRARE vs. laser and of a dedicated time transfer experiment with PRARE are presented.

Keywords: PRARE, ERS-2, Two-Way Microwave Satellite Tracking

1 INTRODUCTION

PRARE (Precise Range And Range-Rate Equipment) is a space-borne, two-way, two-frequency microwave satellite tracking system with onboard data storage and central data preprocessing. This allows data analysis on a global basis within a very short time delay. Due to the microwave transmission concept, the system operates independently from weather and daylight conditions. PRARE has been developed on behalf of the German Space Agency DARA GmbH since the mid-eighties by the Institute for Navigation of the University Stuttgart, later TimeTech GmbH, Stuttgart, the GeoForschungsZentrum Potsdam, and Dornier GmbH, now Nortel Dasa GmbH, Friedrichshafen. Parts of the space segment have been fabricated by Kayser-Threde GmbH, Munich. The complete system has been tested onboard the Russian meteorological satellite Meteor-3/7 between January 1994 and October 1995. Since May 1, 1995, the system is working in redundant configuration onboard ERS-2 [Reigber et al., 1995].

PRARE consists of a space, a ground and a control segment, whereby the ground segment is made up of 29 transportable, autonomously operating and globally distributed ground stations. The control segment is established in Germany and comprises a Master Station (managed by GFZ in Oberpfaffenhofen: network management and support, data preprocessing, data quality control and distribution), a Monitoring and System Command Station (managed by TimeTech GmbH in Stuttgart: space segment control, data dumping), and a Calibration Station (managed by GFZ in Potsdam: periodic calibration of PRARE w.r.t. laser). The system is - after intensive calibration efforts during the commissioning phase lasting from May 1, 1995 until December 31, 1995 - in operational status since January 1, 1996. Since then, a continuous data base consisting of global high quality tracking data is being established.

2 THE PRARE TRACKING SYSTEM

The PRARE measurement signals are based on a combination of high frequency carriers (X-/S-band), appropriate pn-codes (10/1 Mcps/s), and spread spectrum binary data (2/4/10 kb/s). The signals are coherently derived from an ultra-stable quartz oscillator inside the space segment and disseminated by two dipole antennas. The ground stations, which are actually in view of the satellite, receive the X-band signal and demodulate the pn-code. Then the pn-sequence is remodulated onto the X-band uplink and retransmitted to the space segment (regenerative transponding) together with additional ground station data for the later correction of the signals.

As the ground station design is, moreover, coherent, the carrier frequency of the uplink is in a well defined relationship to the downlink carrier. The space segment can, therefore, measure the two-way range and the two-way doppler-shift of the signals very precisely by comparing the phase of the received signal to the phase of the onboard clock (fig. 1). These measurements can be carried out with up to four ground stations simultaneously. The overall accuracy of the system is mainly driven by the fully coherent two-way measurement principle, the high frequencies, and the appropriate resolution of the four space segment receiver counters [Hartl, 1984].

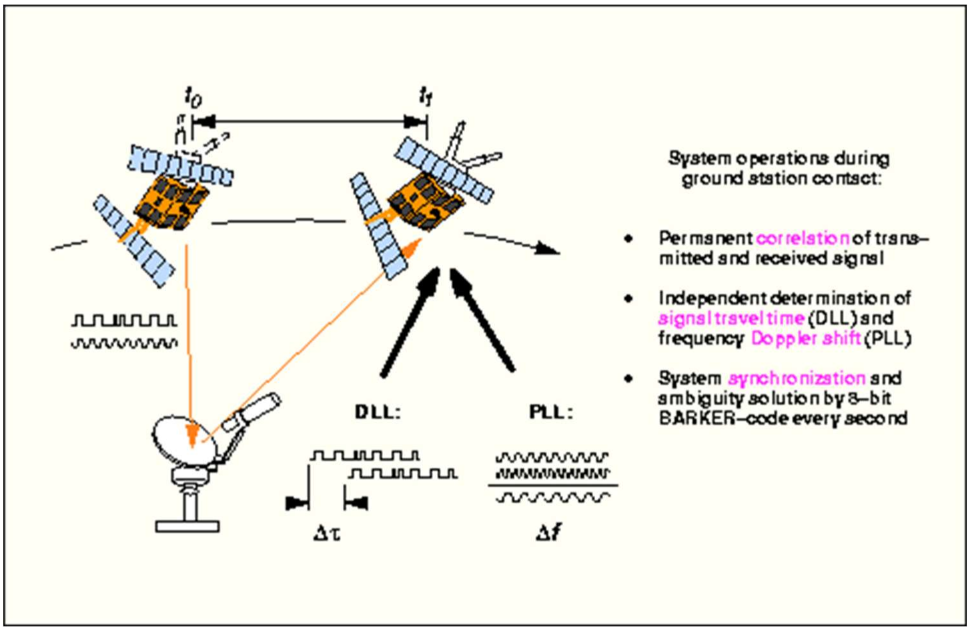

Fig. 1: PRARE measurement principle (one channel out of four).

All generated tracking as well as various corrective data are automatically collected by the space segment and stored highly compressed in the space segment's data memory together with onboard housekeeping and calibration data. During each contact of the satellite with the Monitoring and System Command Station Stuttgart (six to seven times a day), these data are downloaded - superimposed on the routine tracking signal - with a rate of 4 or 10 kb/s, depending on the memory filling rate. These dumped data are forwarded automatically to the Master Station Oberpfaffenhofen for further processing.

At the Master Station, the raw binary data are decoded and transformed into physical chronological quantities for each ground station. The preprocessing procedures determine all known range and doppler corrections due to hardware calibration, measurement principle, geometry and atmosphere. Additionally, the appropriate clock parameters coming from the Master Station time system are applied to transform the onboard time scale to UTC. Besides the tracking informations, the ionospheric measurements (X-/S-signal travel time differences) are preprocessed and the total electron content (TEC) in slant and vertical direction is archived in separate data files [Flechtner et al., 1997]. In a last step, the one-per-second two-way range and doppler full rate data are compressed to 15-seconds normal points and provided to the PRARE data users via the ftp server at the GFZ Data Centre in Potsdam.

The status of the ground station network as well as all relevant tracking and preprocessing statistics are determined weekly and distributed by electronic mail to presently about 70 PRARE-interested users.

2.1 SPACE SEGMENT PERFORMANCE

Among many other checks, a periodic evaluation of the space segment's mean temperature as well as of the frequency offset and drift of the space segment's central oscillator is carried out at the PRARE Master Station. On the one side, this serves to test if these parameters are still within their specified limits to assure the validity of the calibration functions, on the other side, the performance of the system depends on a precise determination of all corrective values to be included in the data preprocessing chain.

Fig. 2 shows the mean space segment temperature, which is part of the periodically downloaded housekeeping data, as measured between May 1995 and March 1997. Up to now, the temperature remained well within the specified limits, and it was changing very slowly throughout the whole mission, which allowed a very smooth tracking data correction. Between JD -1250 and -1180 (August/September 1996), the space segment was operated in so-called "reduced mode", which is characterized by a periodic switch-off of all hardware modules that have no function during the time gaps between ground station contacts. The reduced heat production following these actions can be clearly recognized in the graph: the temperature lowering in "reduced mode" is about 2 degrees C.

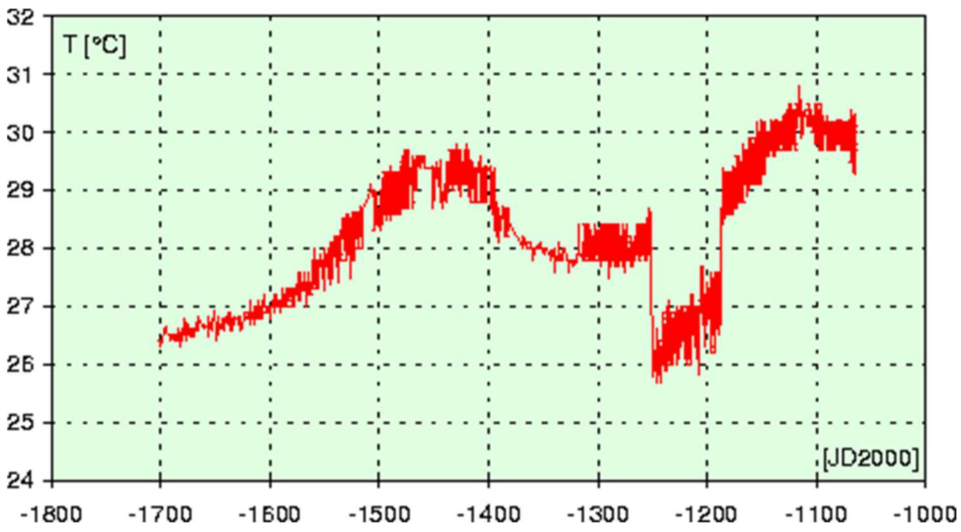

Fig. 2: Mean PRARE space segment temperature between May 1995 and March 1997.

For the period May 1995 to March 1997, the frequency offset and drift of the space segment oscillator, which has been determined within the PRARE time system of the Master Station, is shown in fig. 3. The oscillator ageing is at the same time constant and very small, which indicates a very good performance in view of tracking data generation and time tagging. A correlation with space segment temperature can not be identified, which is another indication for a very stable space segment performance and a high measurement data quality.

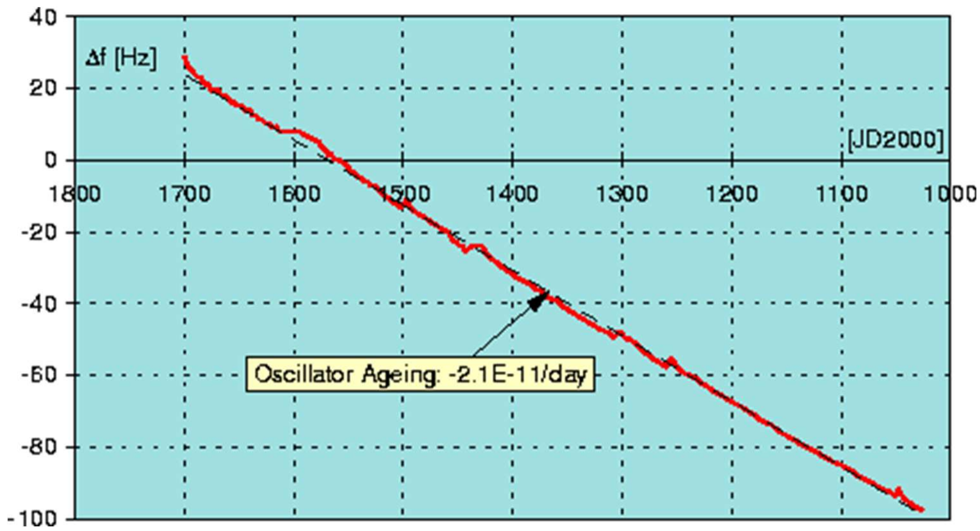

Fig. 3: Frequency offset and ageing of the PRARE space segment oscillator between May 1995 and March 1997.

2.2 GROUND STATION NETWORK

The PRARE tracking network consisting of 29 transportable, autonomously operating ground stations in total is owned and operated by 13 different international user groups. The present network status is shown in fig. 4, including the installation planning up to mid 1997. Many of the PRARE ground stations have been installed at sites which offer colocations with other satellite tracking systems like GPS, Doris, VLBI or SLR. This is used to adjust the respective reference systems as precisely as possible in order to generate a consistent global coordinate reference frame.

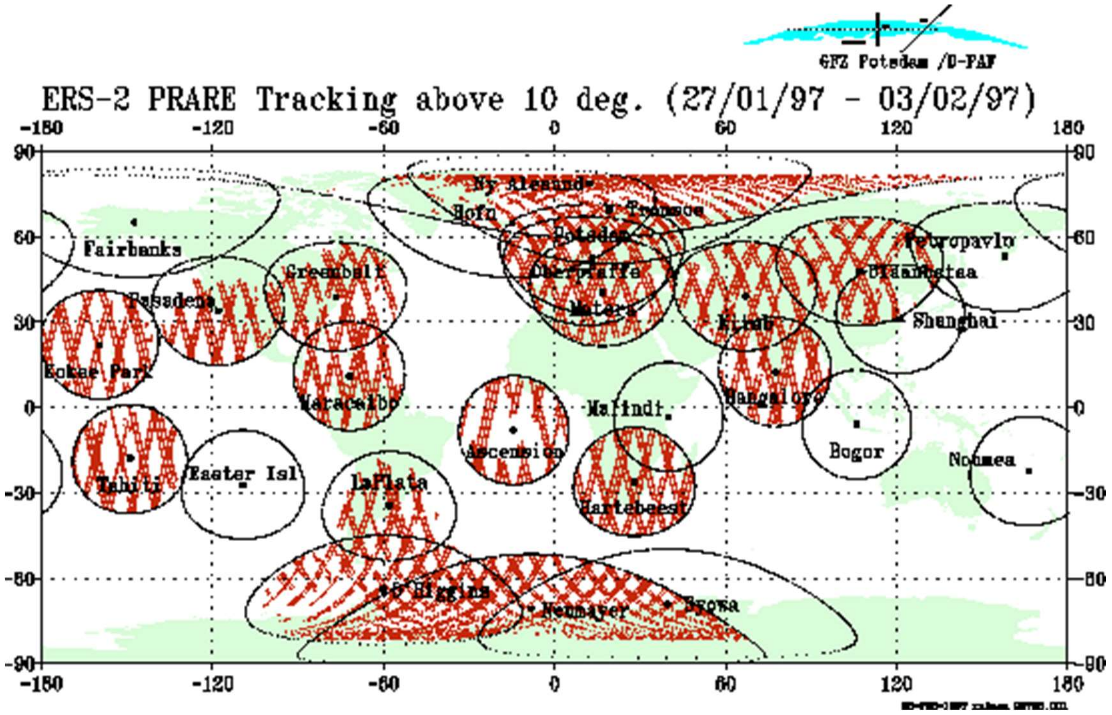

Fig. 4: PRARE ground station network (present status and planning).

The present PRARE tracking network, which consists of around 17 permanently operating ground stations (status spring 1997, cf. fig. 4), acquires nearly 100 passes per day (fig. 5). Due to the ERS-2 orbit inclination, polar stations like Ny Alesund or Neumayer contribute with up to 14 passes per day. The ground stations are tracking from nearly horizon to horizon - as long as no obstructions block the line of sight to the satellite - resulting in average pass lengths of about 600 seconds.

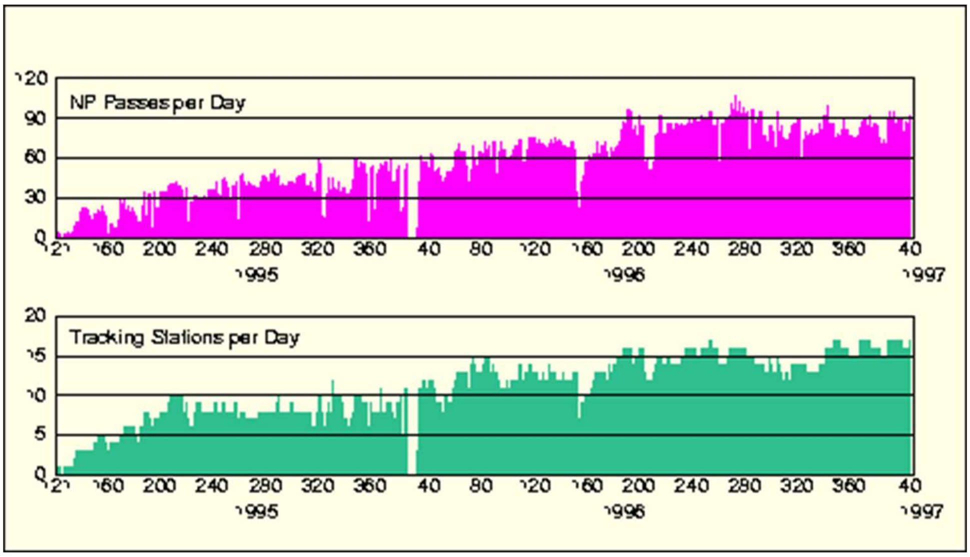

Fig. 5: Daily number of PRARE passes and operational tracking stations between May 1995 and March 1997.

Taking a closer look to the tracking statistics, some periods with reduced or missing data production can be identified. These are due to several instrument respectively payload switch-offs, which occur from time to time and are mainly caused by satellite platform anomalies.

2.3 DATA QUANTITY AND QUALITY

The average amount of tracking data is presently around 300 000 full rate range and doppler data each per week, which corresponds to around 20 000 normal points each per week. After preprocessing, the average noise of the full rate two-way range data is about 2.5 to 6.5 cm depending on the geographical latitude of the ground station and on the percentage of multipathing, for the two-way doppler data an average noise of about 0.1 mm/s is effective (30 seconds integration interval). The normal points' noise is less than 1 cm resp. 0.015 mm/s.

Since January 1, 1996, the data are preprocessed as revision 5 data, which include various corrections covering all systematic effects which have been identified during the data calibration campaigns. The main improvements compared to previous data revisions concern the overall data quality and the space segment and ground station calibration:

a) extended database for internal space segment and ground station calibration;

b) improved modelling of relative and absolute ground station hardware delays;

c) improved ionospheric modelling using the DRVID (Differenced Range Vs. Integrated Doppler) method [Flechtner et al., 1997];

d) better multipath flagging as a result of the DRVID method;

e) for tropospheric delay correction, interpolated meteorological data (pressure, temperature, humidity) instead of standard atmosphere are used in case of missing or corrupt meteo stations, which were derived from monthly mean values along the ERS-2 satellite path provided by the ECMWF (European Centre for Medium Weather Forecast, Great Britain).

3 DATA EVALUATION

As a result of the distinctively extended data base, first long time evaluations could be carried out. Figs. 6a and 6b show exemplarily the weekly standard deviation of the range residuals (w.r.t. a polynomial fit) of the PRARE station Neumayer/Antarctica and its weekly percentage of identified range multipathing. The figures demonstrate that a semi-annual variation of both parametres can be derived, whereat the respective amplitude is closely correlated to the geographical latitude of the station. The period and the phase shift of these time series data is mainly due to the respective position of the Earth and the alignment of the ERS-2 solar panel w.r.t. the Sun throughout the year.

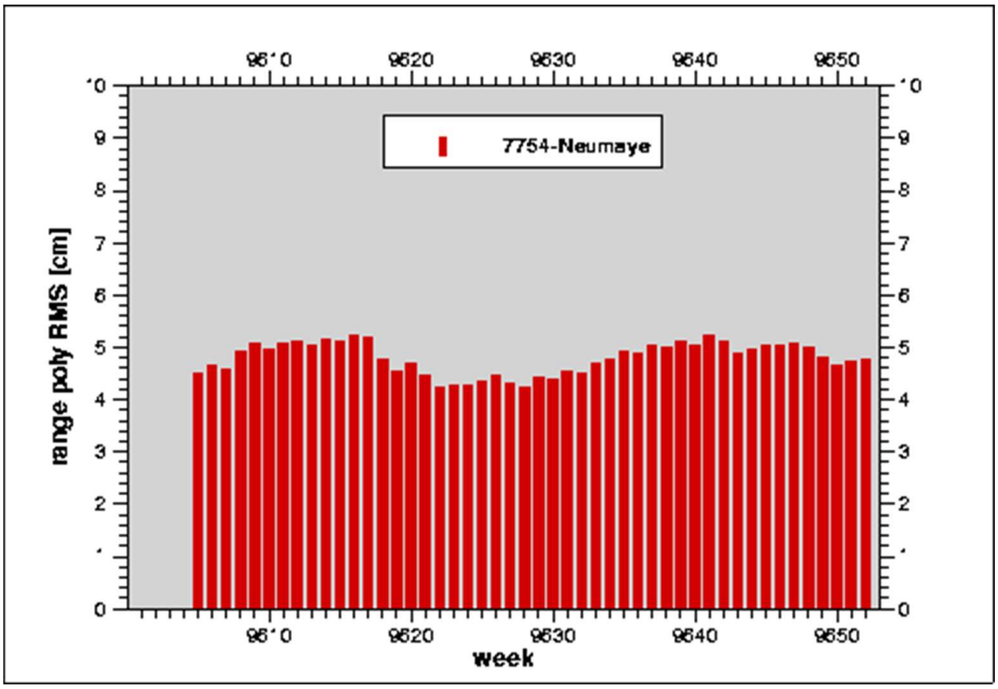

Fig. 6a: Weekly two-way range residuals of PRARE station Neumayer/Antarctica in 1996.

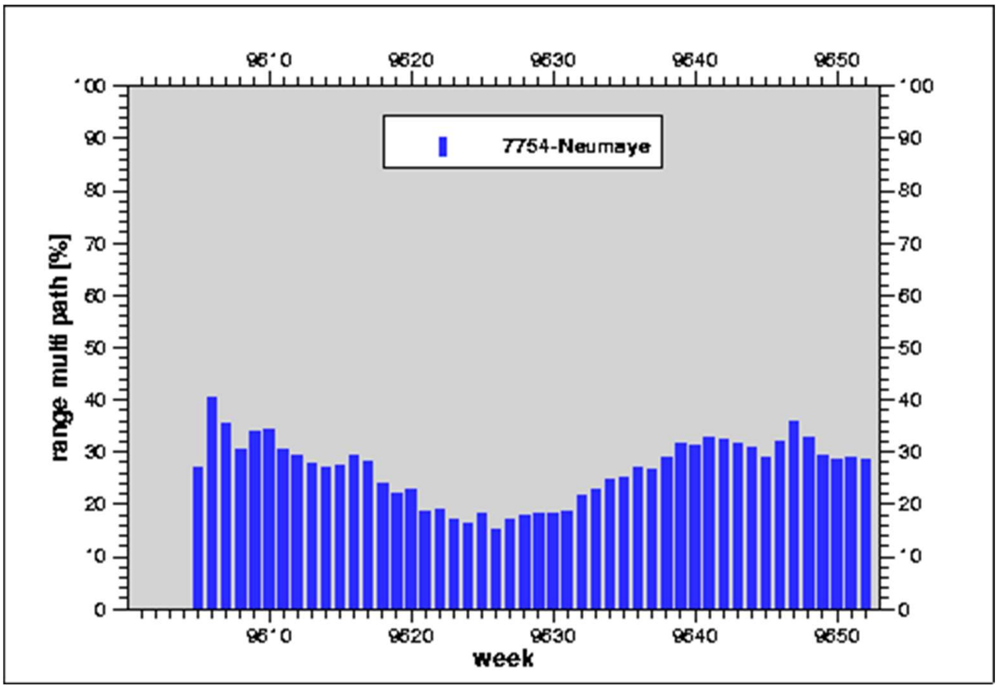

Fig. 6b: Weekly percentage of range multipathing of PRARE station Neumayer/Antarctica in 1996.

3.1 Station Coordinate Solutions

One essential prerequisit for precise orbit determination a well as for other data applications is a profound station coodinate solution. By evaluation of all PRARE range and doppler data, which are available up to now, the most recent set has been derived by GFZ/D-PAF. A summary of the evaluation strategies and corresponding results are to be found in [Massmann et al., 1997].

3.2 Precise Orbit Determination

Since beginning of the system's operational phase (January 1, 1996), PRARE range and doppler data are used by GFZ/D-PAF for precise ERS-2 orbit solutions on a routine basis. In general, the obtained results confirm the constantly high quality of the PRARE tracking data, which is mainly due to the fact that

a) there is no significant time bias beyond the 10 µs level;

b) the station range biases are varying from station to station due to individual equipment and hardware delays, but are constant per station over time;

c) the tropospheric scaling factor is close to one with a variation of only a few percent.

Detailed descriptions concerning orbit determination strategies and appropriate results can be found in [Massmann et al., 1997].

3.3 Ionospheric Modelling

By means of the ionospheric tracking data generated by PRARE during every ground station contact, the total electron content (TEC) along the slant range between the ground station and the satellite, TECs, as well as the vertical TECv at the sub-ionospheric point can be derived. Due to the specific design of the PRARE system, the ionospheric information from the global network is available at the Master Station within a few hours delay, which is a great advantage compared to alternative tracking systems.

In order to use these PRARE derived observations for ionospheric modelling and tracking data correction, the data have - up to now - been preliminarily calibrated and validated. A description of the corresponding evaluation techniques and first results, which show a very promising precision and stability, can be found in [Flechtner et al., 1997].

3.4 External Calibration

For external system calibration, PRARE range data of station 7741 (Potsdam-1, 47 passes) and 7722 (Greenbelt-0, 47 passes), which were acquired mid 1996, have been compared with quasi-simultaneous Potsdam and Greenbelt laser tracking data. The calibration procedure is performed in two steps: after interpolation of the PRARE range residuals onto the time tags of the corresponding laser residuals, the PRARE and laser data can be compared geometrically without the necessity of modelling the satellite movement, because orbit errors are in this case identical for both kind of tracking data. If, moreover, the baseline between the PRARE and the laser station is well known, systematic residuals can be identified.

When adjusting a tropospheric scaling factor per pass for the PRARE range residuals, the comparison results show only very small systematic differences between both tracking data types: for the Potsdam site, a PRARE range bias of -1.3 ± 0.5 cm and a time bias of 1 ± 1 µs was calculated, the corresponding results for Greenbelt were -10.5 ± 0.6 cm resp. 3 ± 2 µs. These results are well within the known accuracy limits of the corresponding reference point coordinates.

3.5 Time Transfer and Clock Synchronization

The very high quality of the PRARE full rate range and doppler data allows - similarly to the procedures carried out by the Master Station time system - to compare the time offset and time drift of ground-based remote atomic standards with an outstanding precision. The according data evaluation process makes use of the internal PRARE synchronization pulses, which routinely serve to maintain time coherency between all the components of the system. They can be accessed at a ground station, where they are generated physically after recognition from the space segment signal. The signals must be fed to a high resolution time interval counter which measures these PRARE 1-pps (one pulse per second) signal against the 1-pps series produced by any common time standard. This alternative usage of PRARE data could become an interesting system feature in times of growing need for global time synchronization.

As the PRARE 1-pps signals are not cleaned from the varying signal delay and doppler shift, which is due to the changing slant range and relative velocity between satellite and ground station, the obtained time difference data must be reduced by means of the appropriately scaled two-way range and/or doppler data, which are routinely preprocessed at the PRARE Master Station. If these reduced data are referenced to the ground clock time scale, offset and drift of the space segment oscillator become visible, if scaled vice versa, offset and drift of the used time standard against PRARE time can be identified. The precision of this clock comparison method is at the nanosecond level, which is mainly based on the inherent high accuracy of the PRARE two-way full rate data. The main residual error source is the uncalibrated generation of the 1-pps signals inside the ground station, which is an unspecified function. By cautious data smoothing it is, however, possible to acquire a time comparison precision of about 1 ns for nearly any satellite pass.

The four parallel receiver channels of the PRARE space segment allow an even more interesting application of the described method: a true Common View time comparison of up to four ground clocks that are simultaneously in view of the space segment is easily achievable. For that purpose, the one-way time difference measurements at each site have to be reduced individually by their preprocessed and adequately scaled two-way data. If these reference data are then correlated mutually, whereby exact synchronism has to be maintained, an again improved precision w.r.t. ground clock comparison is achieved. In a dedicated experiment which has been carried out in winter 1995/96, three time standards, which were available at GFZ Potsdam (Cs clock), DLR Weilheim (H-Maser) and PRARE Master Station Oberpfaffenhofen (Rb clock), have been intercompared by means of the introduced method. The precision of this Common View two-way time transfer was at the sub-nanosecond level , the closed-loop sum of all clock offsets was always correctly at the zero level [Bedrich & Hahn, 1997]. Fig. 7 shows an examplary correlation of the H-Maser time w.r.t. the Rb clock time during a Common View pass based on two smoothing approaches (30 s and 300 s smoothing).

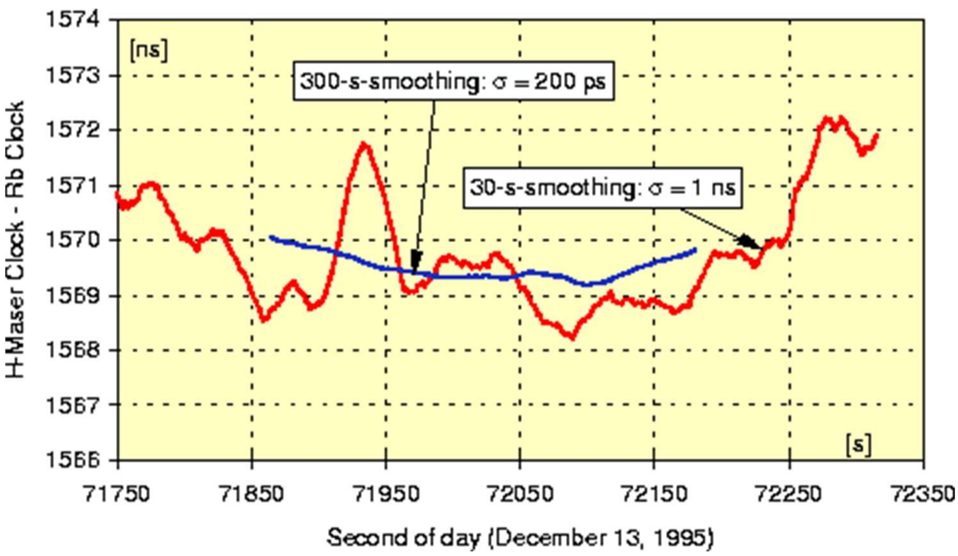

Fig. 7: Residual clock offset between a H-maser (DLR Weilheim) and a Rb clock (GFZ Oberpfaffenhofen) measured via PRARE on ERS-2.

The accuracy of the acquired time offsets was checked with the help of commercial GPS time receivers, which were connected to the atomic clocks and operated in parallel at each site. Due to the known drawbacks of GPS in view of absolute time transfer, the accuracy level for the clock comparison could, however, not be lowered below the 10 ns level [Bedrich & Hahn, 1997]. The obtained results are nevertheless very promising and demonstrate clearly the superiority of the two-way PRARE method compared to one-way GPS time transfer. As data handling is very comfortable due to the PRARE central data collecting and preprocessing concept, further use of this new clock comparison method in future satellite navigation and time transfer systems is highly recommended.

4 CONCLUSIONS

The PRARE system is in continuous and stable operation onboard ERS-2 since May 1, 1995. Diverse intensive calibration efforts covering all system components have lead to improved routines for preprocessing of very precise two-way range and doppler tracking data. These data are routinely generated at the PRARE Master Station and distributed to about ten international user groups regularly along with detailed tracking and system performance statistics. First results with derived higher-level products as for example station coordinate solutions, precise ERS-2 orbits, ionospheric quantities, or time comparison data of remote atomic clocks, prove the continuously high quality of the PRARE data. The very short time delay between actual measurements and availability of the preprocessed data, which is due to the central data handling concept, emphasizes the potential of the PRARE system for future applications in geoscientific and navigation satellite systems.

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