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PRARE In-Orbit Calibration Plan for ERS-2

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PRARE IN-ORBIT CALIBRATION PLAN FOR ERS-2

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1. INTRODUCTION

The microwave tracking system PRARE developed in the Federal Republic of Germany is one payload element of the European ERS-2 mission. This autonomous tracking system with small portable ground units will allow precise two-way, two-frequency range and range rate measurements in almost all weather conditions supporting the radar altimetry as well as other sensors on board by precise and rapidly available orbit ephemeris information. Corrective information such as total electron content (TEC) and meteorological data from the ground stations will be available for all microwave measurements of this mission.

The PRARE microwave tracking system aims to support the mission by fulfilling the tracking requirements with regards to measurement precision, all-weather operation, low costs, automatic operation and transportability. Herewith it shall complement in an optimum way the existing Laser network with its limitations in station distribution, weather dependency, comparatively high costs for operation and additional shifts and the question of priority over other missions.

The processing of the precise ERS-2 tracking data of the global network will be conducted by GeoForschungsZentrum Potsdam (GFZ), Federal Republic of Germany.

The PRARE experiment has the objective to demonstrate the tracking system performance by:

- System test under operational conditions for space segment, ground segment and master ground station to prove the system as an autonomous tracking system
- Accuracy evaluation by comparison with Laser and other tracking systems
- Orbit determination for ERS-2 together with Laser tracking
- Investigation of the total electron content (TEC) of the ionosphere along the transmission path
- Baseline determination for geodetic and geophysical purposes.

Although the PRARE space segment and ground tracking units contain facilities for the determimination of hardware related calibration parameters for each measurement interval, in addition to these calibrations there is a strong reqirement for an calibration procedure to monitor the overall performance of the tracking measurements against most precise Laser systems and to tie the PRARE observations into the International Terrestrial Reference System (ITRF).

The general idea of this calibration procedure is to have comparative measurements to the ERS-2 satellite from the two tracking systems Laser and PRARE installed adjacent at the site of the Potsdam tracking station. The Potsdam calibration site is equipped with one of the best Satellite Laser Ranging (SLR) systems and involved in a great number of international

geodetic and geodynamic projects. Additionally permanent GPS measurements are performed at Potsdam.
The regular calibration measurements and analyses will be executed by GeoForschungsZentrum Potsdam. This way the experiences obtained during the calibration of PRARE onboard of METEOR-3 can be used for ERS-2.

2. CALIBRATION SCENARIO

2.1. Potsdam Station Equipment

The station Potsdam is located at 52°22'53" latitude, 13°04'01" longitude and a height of 93 m. The station is presently equipped (among others) with a

- 3rd generation Nd: YAG Satellite Laser Ranging (SLR) system and
- permanent GPS station included in the global network of IGS

The SLR system is housed in the observation pavilion where the potographic zentih telescope was operated until 1990. It was installed in 1992. Regular observations at this place began in January 1993. Since that time more than 2000 passes from all laser satellites have been obtained. High priority has been given to the European satellite ERS-1 and more recently to the PRARE/METEOR calibration campaign. The statistics of observed passes of METEOR-3 and ERS-1 for 1994 is shown in Figure 2.1.

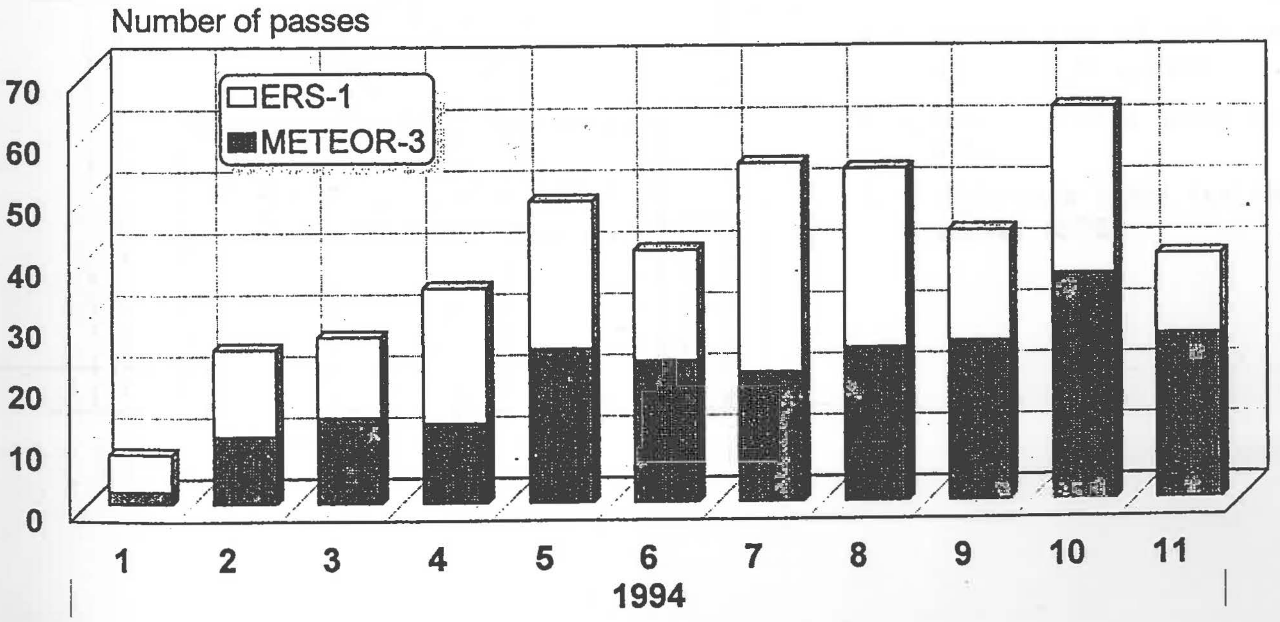
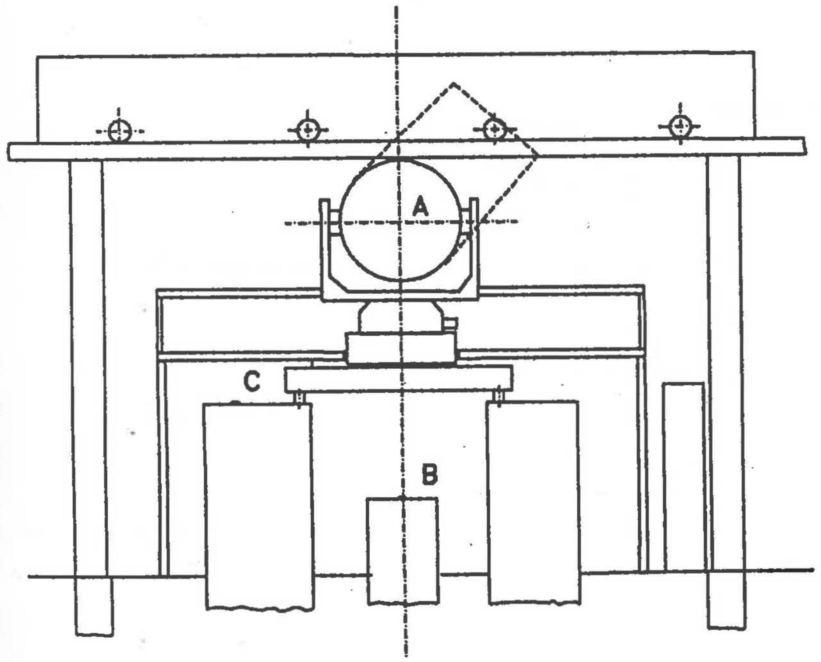


Figure 2.1. Monthly statistics of METEOR-3 and ERS-1 passes tracked by SLR station Potsdam in 1994

The Potsdam SLR system is based on a short-pulse (35ps) Nd-YAG laser of own construction and works with single photon detection in general. The single shot precision for ranging to the single prism calibration target is 8 mm. When ranging to existing satellites, the precision is slightly reduced due to pulse broadening by the reflector array of the satellite. The observed single shot standard deviation for typical satellites is:

LAGEOS:	18 mm
ERS-1 or METEOR-3:	12 mm

The stability of the range measurement over a few hours is better than 2 mm.
The timing equipment for recording the transmission times is based on a cesium frequency standard and an associated GPS-time receiver. This time scale has negligible influence on the range calibration.
The indicated precision of the SLR system has been verified during the PRARE/METEOR calibration campaign in 1994. An indication of the absolute ranging error can be gained from the regular data quality checks performed by the Center of Space Research at Texas University. From the LAGEOS data obtained since August 1994 the average range bias has been found to be smaller than 10 mm. The scheme of the Potsdam system is shown in Figure 2.2.



A – Intersection of both axes of the SLR system

B – SLR reference point on pillar

C – Reference point for local survey (GPS)

Figure 2.2. Schematic arrangement of the Potsdam Laser telescope and the reference points

2.2. The Local Network at the Potsdam Telegrafenberg Area

The local calibration network installed at Potsdam Telegrafenberg consists of three PRARE pillars in the neighborhood of the Potsdam SLR station 7836 (c.f. Fig. 2.3.). The distance between the PRARE stations and the SLR equipment is of about 100 m.
The main PRARE calibration station (COSPAR Number 7730) is on the pillar on the old water tower of Building A31. The height of this PRARE pillar is of about 10 m over the surrounding buildings and forest and has an omnidirectional free view to the horizon.
The two pillars on the roof of building A17 (7740 and 7741) are test sites for the temporary operation of a maximum of three PRARE stations simultaneously, which is planned to use for the additional calibration of PRARE stations one with another.
The coordinate differences between the PRARE pillars and the SLR station 7836 were estimated by using GPS combined with terrestrial measurements. The accuracy of the estimated coordinates is of about 10 mm. It has been verified with range measurements of the SLR equipment to an external terrestrial target installed over a GPS reference point.

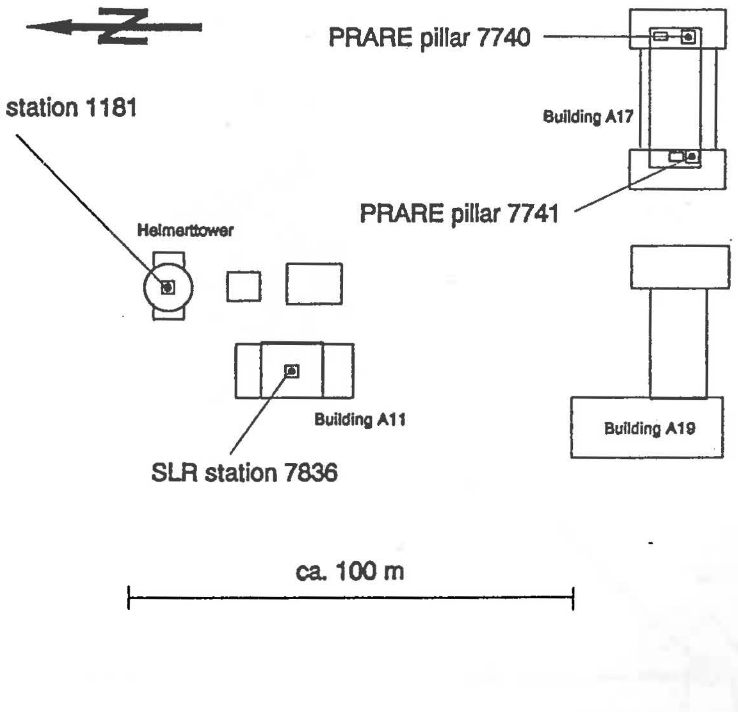


Figure 2.3. Potsdam Telegrafenberg area, the locations of the SLR station and the PRARE pillars

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2.3. Calibration Fundamentals and Geometry

The PRARE experiment team plans are to carry out during the whole ERS-2 lifetime (different intensity during commissioning and exploitation phase) colocation measurements and performance tests by simultaneous tracking of ERS-2 with one or more PRARE transponders and the stationary Laser tracking device. With this procedure it is planned to complete the laboratory tests before launch and the internal calibration measurements in each PRARE component with an overall calibration using the most precise tracking system presently available. As opposed to the laboratory measurements this calibration uses the real tracking configuration and takes into account the refraction influences of troposhere and ionosphere.

The basic calibration geometry is shown in Figure 2.4 with
d_s - difference vector at satellite between the PRARE antenna and the Laser retroreflector
d_g - difference vector at ground between the PRARE transponder and Laser system
l(t) - Laser observation
p(t) - PRARE observation

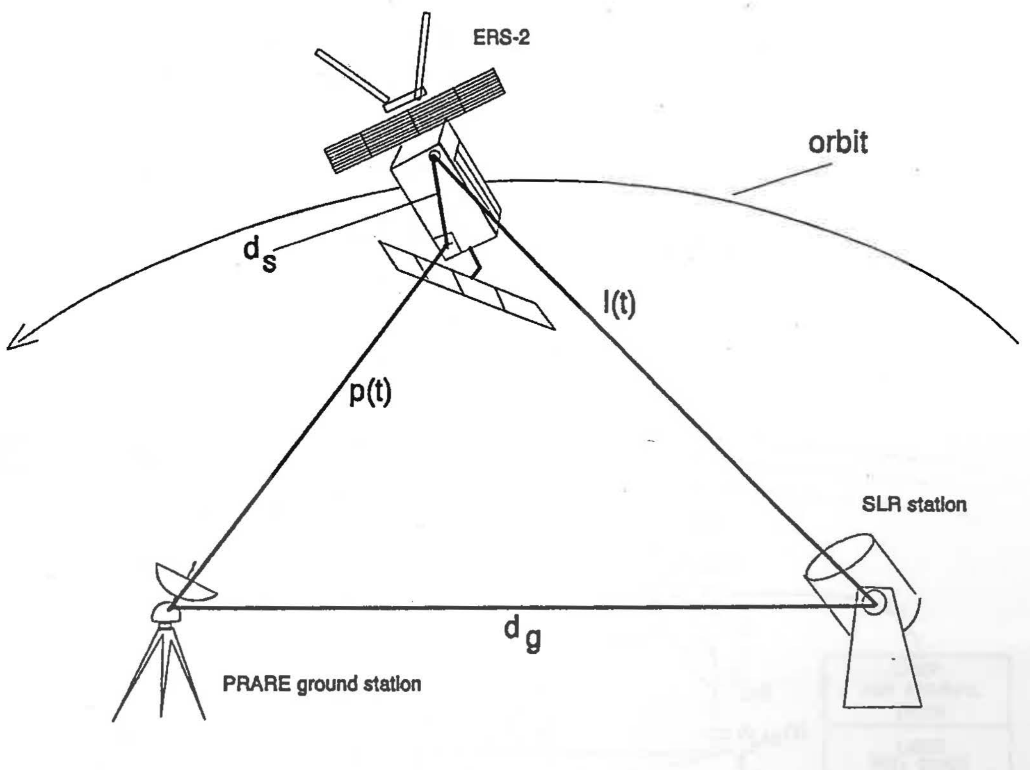

Figure 2.4. PRARE basic calibration geometry

It is the essence of the calibration to compare PRARE range measurements with ranges as measured by the Laser system. Satellite Laser ranging systems, nowadays, comply with high accuaracy standards. Using simple passive retroreflector ground targets they are reliably calibrated in a straightforward manner and their measurements, in contrast to microwave ranging, do not depend on the ionospheric conditions and are much less influenced by the difficult to model water vapour content of the troposphere. Therefore Laser ranging can be considered as a reference for the calibration of PRARE.

The parameters of the basic calibration geometry have to be determined by means of the elements of the arrangement of the measurement systems shown schematically in Figure 2.5. The abbreviations used in the figure have the following meaning:

PSA	- PRARE space segment antenna, phase centre
CG	- satellite centre-of-gravity
LR	- Laser retroreflector, centre of the array
PM	- internal electronic measurement point in the PRARE space segment
PT	- PRARE transponder
PTA	- PRARE transponder antenna, centre of aperture plane, transponder ranging reference point
SLR	- satellite Laser ranging system
LAS	- optical ranging reference point for the Laser range measurements
R	- common reference point in a terrestrial reference frame

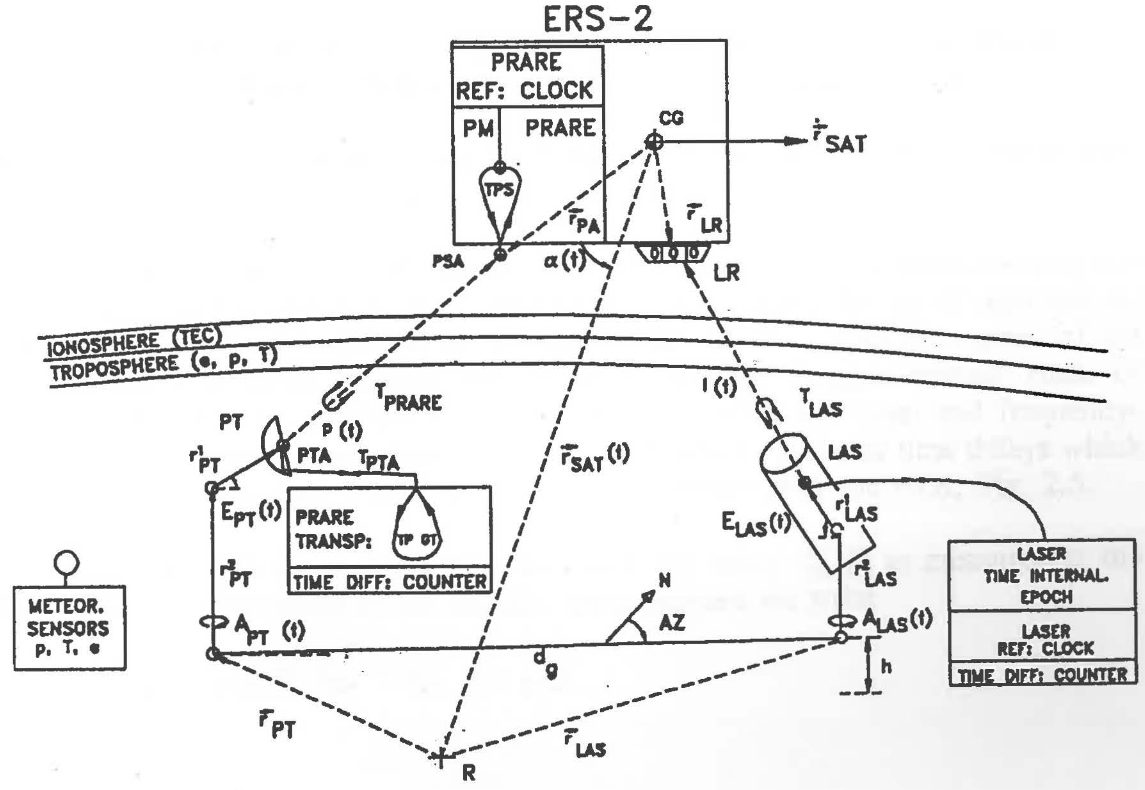

Figure 2.5. Principle of the colocation arrangement

The spaceborne components of both ranging systems are located at different points onboard the spacecraft, outside its centre of gravity. The groundbased instruments of both systems will be operated on different sites on the Potsdam station area. In order to compare the range p(t) as measured by PRARE and the range l (t) as measured by the Laser system, some geometrical corections must be applied to transform them to a common "line of sight".

The relevant geometrical elements are illustrated in Figure 2.5:

$\vec{r}_{PA}$ - vector between the satellite's CG and the phase centre of the PRARE antenna
$\vec{r}_{LR}$ - vector between the satellite's CG and the centre of the Laser reflector array
$\alpha(t)$ - attitude angle
$\vec{r}_{SAT}(t)$ - radius vector between a terrestrial reference point and the satellite's CG
d_g - length of the baseline between the two framed points underneath the vertical axis of the instruments' mounts
AZ - orientation angle of this baseline
Δh - height difference between end points of the baseline
r^2_{PT} - height above ground of the intersection between vertical and horizontal axis of the PRARE transponder mount
r^1_{PT} - distance between ranging reference point PTA of the transponder and the axis intersection
r^2_{LAS} - height above ground of the intersection between vertical and horizontal axis of the Laser telescope mount
r^1_{LAS} - distance between ranging reference point LAS of the Laser and the axis intersection
$A_{PT}(t)$, $E_{PT}(t)$ - azimuth and elevation angles of the axis of the PRARE transponder antenna
$A_{LAS}(t)$,$E_{LAS}(t)$ - azimuth and elevation angles of the axis of the Laser telescope.

Possible errors in the determination of the geometric transformation elements as well as their influence on the calibration results have to be estimated.

Actually, electromagnetic ranging instruments do not measure geometric ranges directly but the two-way propagation time delay of electromagnetic signals along the line of sight and the conversion to ranges is accomplished by multiplication with the propagation speed of the signals. PRARE is a rather complex microwave system and requires several kinds of electronic processing steps, as there are amplification, filtering and code- and frequency-conversion of the signals. All of these are likely to introduce additional time delays which add to the pure two-way path delay τ_{PRARE} between the points PSA and PTA, Fig. 2.5.

Thus, in order to obtain τ_{PRARE} from the total round trip delay τ^{TOTAL}_{PRARE} as measured at the internal measurement point PM of the PRARE space segment we write

$$\tau_{PRARE} = \tau^{TOTAL}_{PRARE} - (\tau_{PS} + \tau_{PSA} + \tau_{PT} + \tau_{PTA})$$

with

τ_{PS} - sum of internal down- and up-link delays in the space segment
τ_{PSA} - sum of down- and up-link delays between antenna reference point PSA and the electronic system of the space segment
τ_{PTA} - sum of down- and up-link delays between the antenna reference point PTA and the electronic system of the ground transponder
τ_{PT} - sum of internal down- and up-link delays in the PRARE transponder

The total of all these equipment delays has to be known to be better than 100 ps in order to guarantee the anticipated ranging accuracy of the PRARE system. τ_{PSA} and τ_{PTA} will be determined in laboratory tests during the prelaunch phase. The more critical internal delays τ_{PS} and τ_{PT} which might depend on the equipment temperature and other operating conditions will be measured in real time in the operational phase of the system by means of testtransponders integrated into the space segment as well as into the ground segment.
The calibration of PRARE with a Laser system will give a good indication on the quality of the measured delay corrections. This was already proved for the PRARE / METEOR Experiment.

2.4. Timing Considerations

The distance between a ground station and the satellite is a function of time. Therefore, in order to obtain comparable ranging results between PRARE and SLR, both systems should be operated, in principle, synchronously. For several reasons this is not feasible. Since the measuring rates are 1 per second with PRARE and 10 per second with the SLR and since the repetition rates of both systems are not locked to each other, there might be arbitrary time offsets of up to 50 ms between the measuring epochs of PRARE- and adjacent SLR-measurements. This corresponds to an alongtrack displacement of the satellite of up to 374 m. For the required transformation of PRARE- and Laser-observations to a fictitious common position of the satellite with an alongtrack error of about 1 cm, the measurement epochs of both systems have to be known to ± 1 μs with respect to a common time frame such as UTC or GPS-time.

PRARE propagation delay measurements and time tagging are effected in the space segment with respect to the PRARE on board clock. The SLR measuring system, in contrast, is based on a cesium frequency standard and on associated GPS time receiver as a reference. The time- and frequency offset between the two systems have to be determined in order to reduce the data.

3. THE CALIBRATION ANALYSIS AND ESTIMATION OF CALIBRATION PARAMETERS

3.1. Theoretical Aspects

The aim of the calibration analysis is the determination of so called calibration parameters. The mathematic definitions should express possible systematical errors in a physically plausible way. For the PRARE Range calibration the following relation is used:

with:

[3-1] $$\varrho_L - \varrho_P = r_B + r_C \cos E + r_S \sin E + t_B \dot{r} + \dot{r}\,(t - t_O) + \dot{t}_B \dot{r}(t-t_O)$$

ϱ_P = PRARE Range observation
ϱ_L = Laser Range observation
r_B = Range Bias
E = Elevation (Angle of the satellite over the local horizon)
t_B = Time Bias
r_C, r_S = elevation dependent Range Biases
t = epoch of measurement
t_O = Reference epoch (for example the time of the beginning of the weekly orbit)
$\dot{r}$ = Range Rate (between station and satellite)
$\dot{r}_B$ = Range drift (Time dependent range bias)
$\dot{t}_B$ = Time Bias rate (Clock drift)

where r_B, r_C, r_S, t_B, $\dot{r}_B$ and $\dot{t}_B$ are calibrations parameters which will be estimated from the comparison of the PRARE range and SLR data. This can be done by fitting the PRARE to the laser observation using a least square adjustment with solving the calibration parameters in according to formula 3-1. But before applying this formula in practical cases it's essential to fulfill two suppositions:

1) In real cases the ϱ_P and ϱ_L values are never related to the same reference points on the ground and the satellite. As pointed out in Chapter 2.3. both different measurement data must be transformed to be comparable. This is possible by adding resp. substracting the projections of the local difference vectors $\mathbf{d}_g$ and $\mathbf{d}_s$ at ground and on the satellite on the directional vector between the ground stations and the satellite. Such transformation algorithm must take into account the following geometrical aspects, which may be different from one measurement time epoch to the next:
   - the coordinates of both the position of the satellite and the colocated ground stations, described in a common reference system. This implies the knowledge of a preliminary orbit of the satellite and the earth rotation parameters,
   - the velocity vector of the satellite,
   - the onboard coordinates of the laser retroreflector, the PRARE antenna phase center

and the satellite center of mass given in a satellite fixed coordinate system,
- the orientation of the (nonspherical) satellite, described in the reference system common with the satellite position and the ground station coordinates.

2) It's practically impossible to obain PRARE and laser data at the same measurement time epochs. That means, it's indispensable to interpolate the PRARE and laser data to the same time epochs.

In priciple the points described above are also valid for the case of the comparison of PRARE Range Rate and laser data with one fundamental difference:
Laser Range and PRARE Range Rate measurements cannot be compared directly. A comparison of these both different measurement types is only possible in an indirect way by forming Range Rate values from the time dependent change of the measured laser ranges (an opposite procedure should not be possible).

3.2. Results from the Calibration of PRARE onboard METEOR-3

A PRARE equipment is currently in operation onboard the Russian weather satellite METEOR-3/7. This SV was launched at January 25 1994 and the PRARE system onboard is in operation since January 31 1994. The orbit of this satellite has a major semi axis and an inclination of about 7580 km and 82°, respectively. The payload of METEOR also contains a laser retroreflector; the satellite is continuously tracked by the world wide SLR station network. Due to its orbit and the construction of the retroreflector the SLR observation conditions of METEOR are very similar to ERS-1 and ERS-2.

The PRARE groundstation network for METEOR consists of about 10 sites, most of them are installed in Europe.
For the calibration of the PRARE Range data the Potsdam SLR station has been used. It has been performed continuously since the switch-on of the PRARE equipment onboard METEOR. Fig. 2.1. shows a statistics of the monthly observed METEOR-3 passes, together with the ERS-1 passes.

In general the calibration analyses are weekly done and as calibrations parameters one range and time bias are estimated per pass. Fig. 3.1. is a typical example of a calibration pass. It shows the rest residuals between the laser and PRARE range measurements of a passage from February 1994 after the adjustment of a range and time bias. In that example the range and time bias values are of amounts of 20 cm and 48 ms respectively. The noise of the fit is 2.5 cm. These values are typical for all calibration results obtained since the beginning of the mission. The low noise between the SLR and PRARE range measurements shows, that the internal precision of the PRARE system should be at the centimeter level and so be comparable with the best laser systems.

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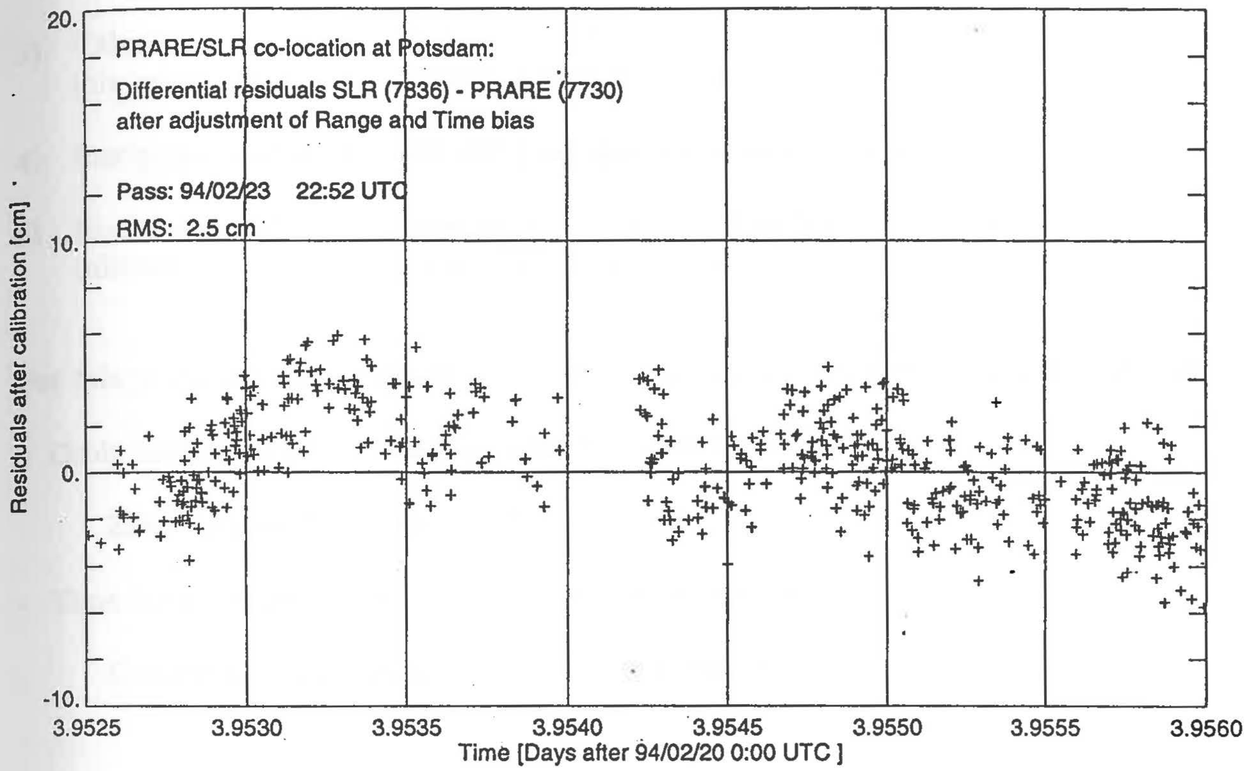

Fig. 3.1. Differential residuals between SLR and PRARE Range from a colocation at Potsdam

4. CALIBRATION PROCEDURE AND SCHEDULE

4.1. Calibration Procedure

At GFZ the calibration analysis is done in the following way in according to the theoretical basics described above:

1) Prepocessing of PRARE raw data and generation of PRARE Range and Range Rate products,

2) Orbit integration including the adjustment of orbital elements for the ERS-2 satellite; the following data are used:

   - the Laser ranging data from the worldwide SLR network as normalpoints,
   - the full rate Laser data from the Potsdam SLR station,
   - the PRARE Range and Range Rate products generated from the PRARE measurements in Potsdam,

3) Calculation of the orbit related residuals of the Laser and PRARE measurements, this values serve as the geometrically transformed data as described above,

4) Interpolation of the PRARE and Laser data to the same time epochs,

5) Performing differences between the Laser and PRARE data and estimation of calibration parameters by a least square adjustment.

For this procedure a combination of the following GFZ written software systems are used:

- Orbit integration and calculation of the Laser and PRARE residuals:

  EPOS (Earth Parameter and Orbit System)

- Time interpolation and calibration parameter adjustment:

  CALPRA (**CAL**ibration of **PRA**RE measurements)

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4.2. Calibration Schedule

The Range and Range Rate Calibration will be carried out during the commissioning and exploitation phases of the PRARE equipment in the following way:

a) **Commissioning phase** (up to three months after switch on of PRARE):

- Executing an intensive calibration campaign of the PRARE stations and the SLR station in Potsdam. In case of good weather it should be possible to obtain about 10 calibration passes per week.
- Performing of simultaneous PRARE measurements of two or three PRARE stations in Potsdam, especially for calibration of PRARE stations one with another.
- Further non-European SLR stations can be included in the calibration program if colocations with PRARE ground stations are realised there, for instance at Ft. Davis or Greenbelt.

b) **Exploitation phase:**

- The calibration schedule after the end of the commissioning phase depends on the calibration results of the first months of the operation of PRARE. That means, according to the results found for the stability of the PRARE system the further calibration plan will be settled.
- The estimation of the calibration parameters will be organised as a permanent service by the PRARE and SLR teams of the GFZ Potsdam.

5. CALIBRATION AND VALIDATION OF ERS-2 PRARE IONOSPHERIC PRODUCTS

5.1. Generation and Distribution of ERS-2 PRARE Ionospheric Products

The procedure to perform one-way travel time delay measurements in X- and S-band is as follows:

The difference of the two simultaneous transmitted down-link signals is a direct measure of the slant total electron content (TEC) of the ionosphere along the transmission path. This measurement is performed 1/sec and is available in the connected monitor & test computer at the ground station and in the PRARE space segment every 4 seconds as an averaged value.

$$[5\text{-}1] \qquad TEC_s = \frac{c}{40.25}\left[\frac{1}{f_S^2}-\frac{1}{f_X^2}\right]^{-1} \Delta\tau_{SX}$$

where

$\Delta\tau_{SX}$ - S - X band ionospheric traveling time difference
f_X - nominal X-band frequency (8.489 GHz)
f_S - nominal S-band frequency (2.248 GHz)

The vertical TEC can only be derived using some approximation formulas [Jopek, 1990]. Using the auxiliary angles in Figure 5.1

$$[5\text{-}2] \qquad z_s = \arcsin\left[\frac{R_o}{r_s}\cos(el)\right]$$

resp.

$$[5\text{-}3] \qquad z_S' = \arcsin\left[\frac{R_o}{R_o + h_d}\cos(el)\right]$$

where

R_o - geocentric radius of the ground station antenna
r_s - geocentric distance of the satellite antenna
h_d - height of the lower ionoshere boundary
el - elevation angle of the satellite above the horizon.

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Then the vertical total electron content is given by

[5-4] $\mathrm{TEC}_v = \frac{1}{2}\mathrm{TEC}_s\,(\cos z_s + \cos z'_s)$ [electrons / m^2]

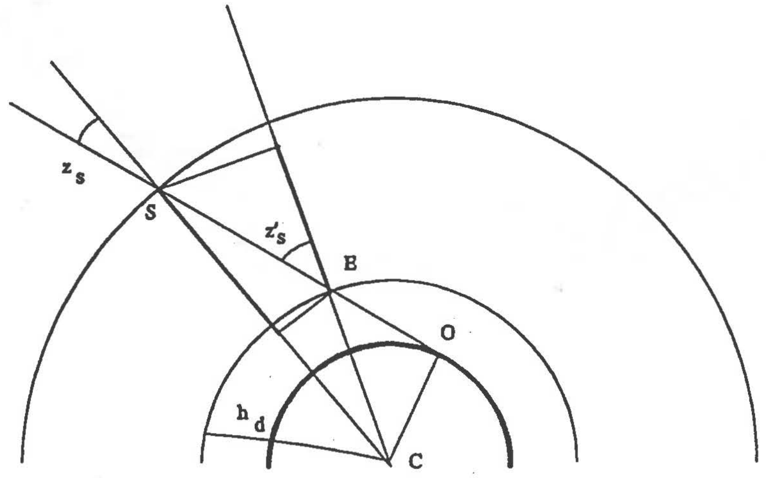

Figure 5.1. Geometric relationship for vertical TEC

In Figure 5.1 the geometrical relationship between slant and vertical TEC is described. S is the satellite, O the observing ground station, C the center of the Earth. The observed slant TEC corresponds to the distance SE.

The ionospheric measurement is performed by comparing the demodulated 10 MHz PN-code of the X-Band with the 1 MHz PN-code of the S-Band. The accuracy of that time difference is better than 1.0 nsec which is due to the noise of the used S-band.

Figure 5.2 shows an example of X/S travel time delays measured in Oberpfaffenhofen May 11, 1994 using PRARE/METEOR-3 data.

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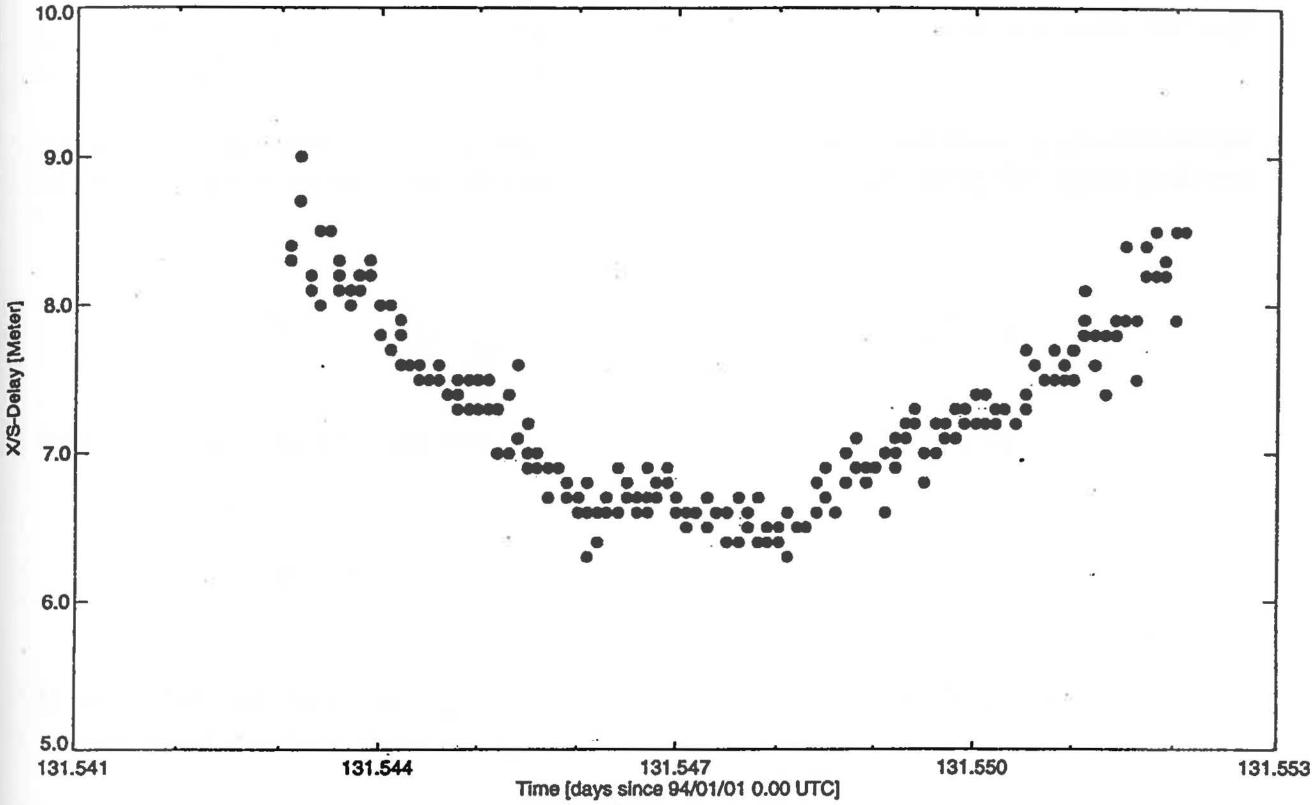

Figure 5.2. Example of PRARE/METEOR-3 X/S travel time delays

PRARE ionospheric products will be available after end of the PRARE commissioning phase about 2 to 4 days after taking of the measurements. The data can be accessed on two ways:

a. On the D-PAF FTP-Server in Oberpfaffenhofen as every ERS-2 ESA global product

b. On an FTP-Server at the GFZ/DC in Potsdam where also the range and doppler data are available for the ground station owners

The data are stored in a UNIX compressed form using a defined directory structure.

5.2. Calibration using Common View Technique

The two used X- and S-band signals will not be transmitted at the space segment simulataneously. In reality there will be a constant bias which has to be calibrated. Additionally in the ground stations the measurement of the travel time delay between two received signals can have a systematic error which has also to be corrected. Because both errors - at the space segment and at the ground station - are totally correlated one can only determine the common effect.

In the following a technique should be described which has also been used in a similar way to calibrate GPS TEC measurements [Ciraolo, 1993].

Starting from the observed travel time delay $\Delta\tau_{SX}$ which is observed in every ground station influenced by the the unknown bias $\Delta\tau_B$ the total electron content along the signal path can be written as

$$[5\text{-}5] \qquad TEC = \frac{c}{40.25}\left[\frac{1}{f_S^2}-\frac{1}{f_X^2}\right]^{-1}(\Delta\tau_{SX}+\Delta\tau_B) = k_1\,(\Delta\tau_{SX}+\Delta\tau_B)$$

This TEC value can be transformed into the vertical (c.f. chapter 5.1) by

$$[5\text{-}6] \qquad TEC_v = 0.5\;k_1\;(\Delta\tau_{SX}+\Delta\tau_B(i))\;(\cos z+\cos z')$$

If more than one station is in visibility of the satellite this vertical TEC can be determined several times assuming quasi-simultaneously observations.

$$[5\text{-}7] \qquad TEC_v(i,j) = 0.5\;k_1\;(\Delta\tau_{SX}(i,j)+\Delta\tau_B(i))\;(\cos z(i,j)+\cos z'(i,j))$$

where

i = 1,n and n = number of simultaneously observing ground stations
j = 1,m and m = number of quasi-simultaneously performed measurements at epochs j

Beside random measurement errors and model uncertainties in generation of the vertical TEC from slant TEC all individul TEC_v at the same moment of time should be the same in a first order approximation. Using this restriction it is possible to calculate individual bias $\Delta\tau_B(i)$ for all stations and/or a common bias for the space segment by least squares adjustment.

5.3. Calibration using Faraday Rotation Measurements

Measurements of the ionospheric total electron content TEC can be obtained from the Faraday rotation that linear polarized radio waves from geostationary satellites suffer when crossing the ionosphere. Dependent on the electron density and on the intensity and direction of the geomagnetic field the polarization plane is rotated by the so called Faraday angle. This rotation can be used to derive the corresponding TEC along the transmission path [Sardon et al., 1993].

A PRARE ground station will be installed in Hobart/Australia where also Faraday rotation observations will be performed during the ERS-2 mission. Therefore it will be possible to compare TEC derived by both systems if both measurements are performed at the same time. Additionally the observations have to be transformed to common sub-ionospheric points in case that the geostationary satellite and ERS-2 will be observed with different elevations. This experiment will be performed in close cooperation with the DLR Neustrelitz.

5.4. Calibration by Comparison with GPS derived TEC values

It is proposed to perform calibrations of PRARE-derived TEC with respect to GPS mesurements. The GPS is suitable for this calibration, because GPS data are available from many ground stations for nearly any time. Furthermore, since GFZ is one of the IGS analysis centres, acquisition of these data presents no additional effort and the decoding and evaluation algorithms are operational.

The very good any-time global coverage provided by the constellation of GPS satellites and the well distributed GPS receivers will permit to analyse individual PRARE passes comfortably. In many cases, where a PRARE station is colocated with a GPS receiver nearly identical lines-of-sight will be available - though only in short time intervals.

Therefore both, a global and a passwise comparison between PRARE- and GPS derived TEC will be performed. The passwise comparison will be done for several PRARE ground stations to detect a possible dependence in the equipment. For single passes however also systematic effects on GPS-satellites must be considered. Additionally it has to be taken into account that GPS measurements - against PRARE / ERS-2 - are also effected by the plasmasphere. Differences between both results can therefore be taken to understand and model this part of the atmosphere.

5.5. Validation by Comparison with Regional Derived Empirical TEC Models

Since many years single and dual frequency methods are applied to model the Ionosphere. Because all this methods are restricted in space and time the International Reference Ionosphere 1990 [Bilitza, 1990] recommended by the Comittee on Space Research (COSPAR) has been developed. IRI90 is based on all important ionospheric data sources including ground based and spacecraft measurements. It provides monthly predicted mean values for the state of the ionosphere (plasma temperatures, electron density, chemical composition etc.). One modul can be used to derive TEC90 analytically on a global basis.

Several investigations have shown that this global model is not able to produce correct TEC values describing the day to day variations especially in times of high solar activity. The prediction error in these model is typically 25 percent of the real TEC.

Therefore in the last years more and more activities started to develope regional models which will have not the disadvantages of the global models. One has to mention for example the PRIME project (Predicted Retrospective Ionospheric Mapping for Europe) where the European ionospheric state should be described between 40 and 60 degrees latitude. Also the DLR in Neustrelitz has calculated a regional model using Faraday rotation and differential GPS measurements. It takes into account the semidiurnal, diurnal and annual dependencies as well as the solar cycle and the latitude of the observing site [Jakowski, Jungstand, 1993].

Fitting PRARE observations into this regional model it should be possible to investigate the quality of the PRARE derived TEC values. This means the determination of bias values and the analysis of temporal dependency (day/night and summer/winter).

5.6. Validation using PRARE derived TEC to correct ERS-2 Altimeter Observations

On ERS-2 a single frequency 1-way altimeter working on ku-band is operated. The ionospheric path delay correction which has to be added to the altimeter ranges is computed by [Rummel, 1992]:

$$[5-8] \qquad Corr_{ion}[mm] = -40250\frac{TEC}{f^2}$$

where

TEC - total electron content [electrons/m^2]
f - altimeter frequency (13.5 GHz).

The total electron content can not be computed directly due to the missing second frequency. Therefore the international reference ionosphere 1990 is used. Because of the disadvantages mentioned in the previous chapter we will therefore use the PRARE derived vertical TEC instead of IRI90 model values for the generation of altimeter data products if ERS-2 is in the visibility of a PRARE ground station. If no station is in visibility one has to interpolate between two sites. Sufficient interpolation methods have to be discussed.

5.7. Calibration by Comparison with TOPEX derived TEC values

Finally we will compare the TEC values observed with the dual-frequency altimeter (Ku-band, C-band) operated on TOPEX with the PRARE ionospheric data. The TOPEX TEC data are a direct measure against which the PRARE data are derived by scaling of the slant

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TEC to the vertical. Both data wil have a difference in time tag so that a temporal scaling method has to be applied.

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