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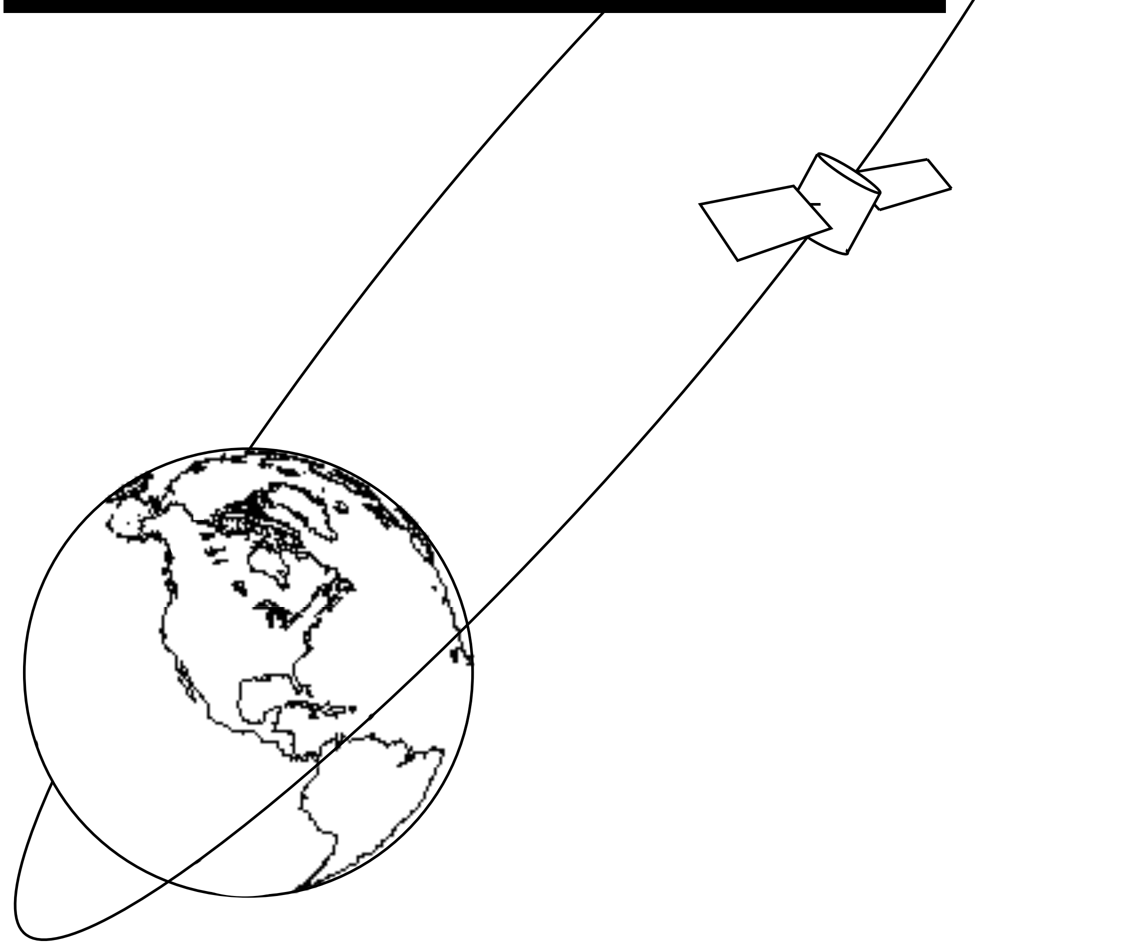
TECHNICAL MEMORANDUM

PRECISE ORBITS FOR ERS-1 USING LASER RANGING AND ALTIMETER CROSSOVERS

John Ries, John Bordi and Tim Urban

March 1999 CSR-TM-99-02



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by

J. C. Ries, J. J. Bordi and T. J. Urban

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PRECISE ORBITS FOR ERS-1 USING LASER RANGING AND ALTIMETER CROSSOVERS

Introduction

Precise orbits for the European Remote Sensing satellite (ERS-1) have been produced by the Center for Space Research in support of the U.S. World Ocean Circulation Experiment (WOCE) studies, as well as the NASA EOSDIS PODAAC at JPL, the NASA Oceans and Ice Pathfinder Data Centers at GSFC, Alaskan SAR Facility, and other scientific investigations requiring precise ERS-1 orbits. The precise knowledge of the height of an altimeter satellite is critical to maximizing the usefulness of the altimeter height measurements. Through improvements in the orbit determination procedures and models, a radial orbit accuracy on the order of 5 cm has been achieved using a combination of satellite laser ranging (SLR) and altimeter crossovers.

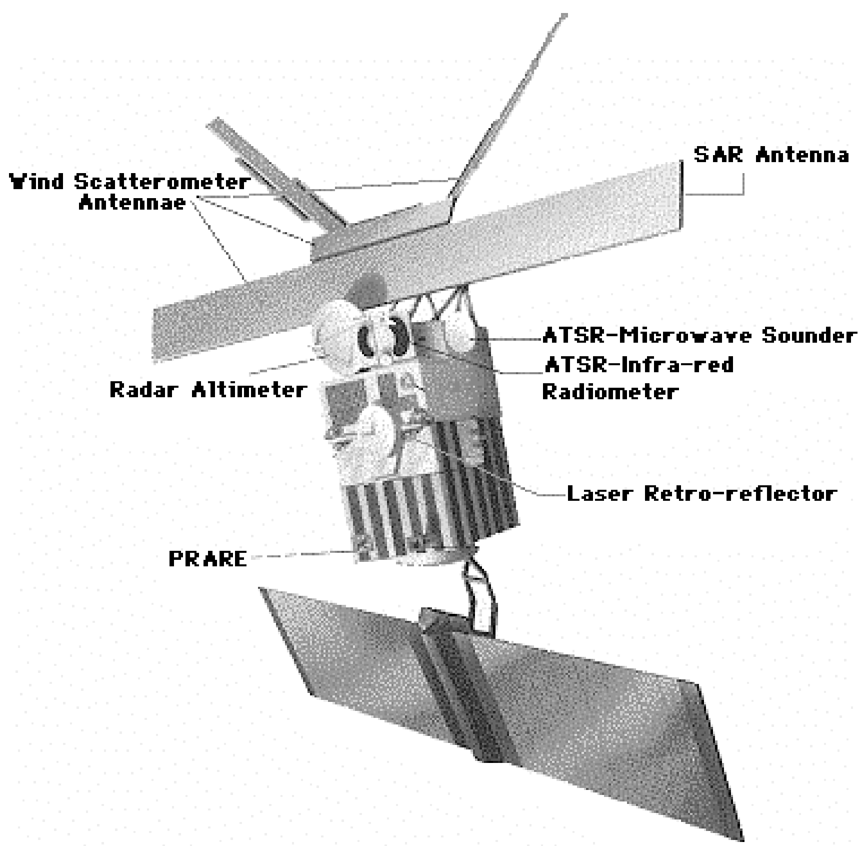

Figure 1. The European Remote Sensing Satellite (ERS-1 and ERS-2)

Orbit Determination

The current set of published trajectories are valid for ERS-1 Phases A, B, C, D, E, F and G. The orbits are determined using a set of models similar to those used for the TOPEX/POSEIDON (T/P) altimeter satellite (Tapley et al., 1994). An important exception is the use of the TEG-3P gravity model rather than the JGM-3 model (Tapley et al., 1996) used for T/P. The TEG-3P model is derived from the TEG-3 model (Tapley et al., 1998) tuned with the addition of PRARE (Precise Range and Range-rate Equipment) tracking data from ERS-2. The PRARE system was first flown on ERS-1 to support precise orbit determination (Wilmes et al., 1987), but the on-board component of the system failed soon after launch. PRARE is currently working very successfully on ERS-2, and an improvement to the gravity model has been possible (Bordi, 1999). This benefits both ERS-2 and ERS-1 since they are in identical orbits. The JGM-3 model used for T/P included no tracking data from ERS-1 or ERS-2, and only a very small amount of tracking data from the STELLA satellite, which is in an orbit similar to ERS-2. Thus the JGM-3 model does not perform as well as the tuned model for ERS-1 or ERS-2. Scharroo and Visser (1998) using ERS-1 altimeter data performed a similar tuning. However, the TEG-3P model, using PRARE data from ERS-2, has reduced the contribution of the gravity model errors to the sub-2 cm level, resulting in radial orbit accuracies at the 3-4 cm level for ERS-2 (Bordi, 1999). For ERS-1, without the benefit of the PRARE tracking, the radial orbit errors are estimated to be limited to the 5-cm level. Similar to T/P, the CSR 3.0 ocean tide model (Eanes and Bettadpur, 1996) is used to model the dynamical effect of the ocean tides on the orbit and for the corrections to the altimeter data. See Appendix 1 for additional details of the corrections applied to the ERS-1 altimeter data used in the orbit determination (see also Urban, 1999).

After the early failure of the PRARE system on ERS-1, it was clear that additional tracking was required to obtain the highest accuracy orbits. The SLR tracking data are of high quality, but the number of passes obtained each day is limited by weather, manpower scheduling at each station and the limited distribution of SLR tracking stations. However, augmenting this tracking data with the altimeter data itself, used in both the standard 'single-satellite' mode and in the 'dual-satellite' crossover mode with the very precise T/P altimeter data, provides significant orbit accuracy improvement (Shum et al., 1990; Visser, 1993; Kozel, 1995). Since T/P was not launched until after the ERS-1 mission started, it is not possible to directly cross ERS-1 altimeter data with T/P altimeter data during some periods. However, it was shown that using the sea surface determined by T/P during the matching season of the year, the same benefit could be obtained as with a true crossover. This was the technique used for the ERS-1 dual-satellite crossover data. The relative weighting of the various data types was determined experimentally. The final choice was a standard deviation of 10 cm for the SLR data (with less accurate stations being downweighted further), 15 cm for the single-satellite altimeter crossovers, and 100 cm for the dual-satellite crossovers.

The trajectories were computed dynamically, estimated over nominal arc lengths of 6 days. This arc length provides adequate tracking data without excessive buildup of orbit errors due to mismodeled surface forces. However, orbits were not fit across maneuvers, so the arc lengths will vary accordingly. The thrusts associated with the maneuvers can cause rapid changes in the position and velocity of the satellite which are difficult to model accurately. It was decided to maximize the orbit accuracy between the maneuvers by breaking the arcs at each of the thrusting events.

To prevent the residual surface force model errors from degrading the orbit, these errors must be accommodated in some way. Previous analyses indicate that estimating an empirical along-track acceleration which varies with a period of one-cycle-per-revolution (1-cpr) is very effective in removing secular errors in the orbital eccentricity and perigee, which maps directly into the radial orbit error [Ries et al., 1993; Tapley et al., 1994]. The estimation of an empirical 1-cpr cross-track acceleration is effective in removing secular errors in the orbital node and inclination, which, although not critical for the orbit height, is important for the high quality fits. The frequency that these parameters are estimated (i.e., the sub-arc length) is a function of both the amount of tracking available and the amount of variability in the dynamic model errors which are manifested as 1-cpr orbit errors. As a result of a number of experiments, the nominal set of estimated parameters chosen for the ERS-1 orbit determination consists of the initial conditions, the drag coefficients (Cd) with a sub-arc length of 6 hours, and empirical 1-cpr along-track and cross-track accelerations with a sub-arc length of 3 days.

Orbit Smoothing and Interpolation

Because orbit continuity (particularly in the radial direction) is critical to avoiding artifacts in the altimeter data, additional efforts were made to minimize the discontinuities during the transition from one orbit fit to the next. Where the independent arcs were not interrupted by a maneuver, the arc end points were chosen such that there was 0.5 days overlap. This minimizes the discrepancies between the arcs at the transition from one arc to the next since some tracking data is used by both orbit fits. Any remaining discontinuity is then eliminated through a blending procedure (Seago, 1997). The removal of the discontinuity between arcs is important not just for the altimeter, but also for proper behavior of the interpolator in the vicinity of the arc breaks. For ease of use, the blended orbits have been provided on a day-by-day basis.

Ephemeris Quality

The radial orbit accuracy for these ERS-1 orbits varies. The average SLR residual RMS for the Phase C, D, E, F, and G orbits is approximately 3 cm, and the ERS-1 (single-satellite) altimeter crossover residual RMS is approximately 7 cm (the time differences between ground track crossings is restricted to be less than the arc length of ~6 days). The Phase C orbits are estimated to be accurate at about the 7-8 cm level initially, improving to the 5 cm level for the remaining part of Phase C and the later phases. The orbits for Phases A and B are considerably worse, at the 10-25 cm level, due to large numbers of maneuvers, sparse SLR tracking and altimeter data which appears to have many problems. The orbits and altimeter data during these two phases should be treated with caution. Additionally, there was no altimeter data available for the last part of phase G, so the orbits during that period were calculated based on SLR data only. These orbits are likely to be less accurate than orbits where altimeter data was available, but it is difficult to assess the accuracy without the altimeter data.

For a variety of reasons, some short portions of the ERS-1 orbits will be considerably less accurate than others. For example, there may have only been a very short span between maneuvers (sometimes less than 1 day) with little or no SLR tracking or altimeter data. There is also the possibility that the orbit immediately in the vicinity of a maneuver may be affected. In some cases, there was simply too little SLR data or serious problems with the altimeter data, resulting in orbits whose quality were difficult to judge. Based on various quality tests and intercomparisons, suspicious parts of the orbit have been flagged, and the interpolating software returns an indicator that can be used, if desired, to avoid using the orbits during the flagged intervals. The orbits during these intervals should be used with caution; they are not always bad, but the probability that they are is greatly increased.

The TEG-3P ERS-1 orbits have been compared to orbits computed by the Delft University of Technology (DUT) and to the orbits from the German Permanent Archiving Facility (DPAF). For most of Phase C and later, the RMS radial agreement is approximately 3 cm with the DUT orbits and 6 cm with the DPAF orbits (see Appendix 2 for further information regarding the DPAF orbits). The agreement is a little worse in the first few cycles of Phase C, at 5 cm with the DUT orbits and 7 cm with the DPAF orbits. While not critical for altimeter applications, the RMS was typically in the range of 15 to 25 cm for the along-track and cross-track differences with the DUT orbits. These results are based on the portions of the CSR and external orbits that were considered reliable (i.e., unflagged). Due to the lack of external orbits and the poor orbit quality, no comparisons were performed for Phases A and B.

Figure 2 illustrates the estimated magnitude of the component of the radial orbit error predicted by the TEG-3P covariance that is geographically fixed. This error is a particular concern for altimeter missions, since averaging many passes of data does not reduce this error. With TEG-3P, the geographically correlated error has an RMS of only 1.2 cm, a maximum less than 2 cm, and an overall contribution to the radial orbit error of 1.6 cm. There are still vestiges of the larger correlated orbit errors over some regions of the world, which are the result of insufficient tracking in these regions, but the magnitude is considerably reduced compared to the JGM-3 or TEG-3 models. Note that this is a 1-sigma prediction based on the TEG-3P covariance. This covariance is considered to be a reasonably accurate representation of the errors, but the true error may be somewhat larger or smaller than this estimate.

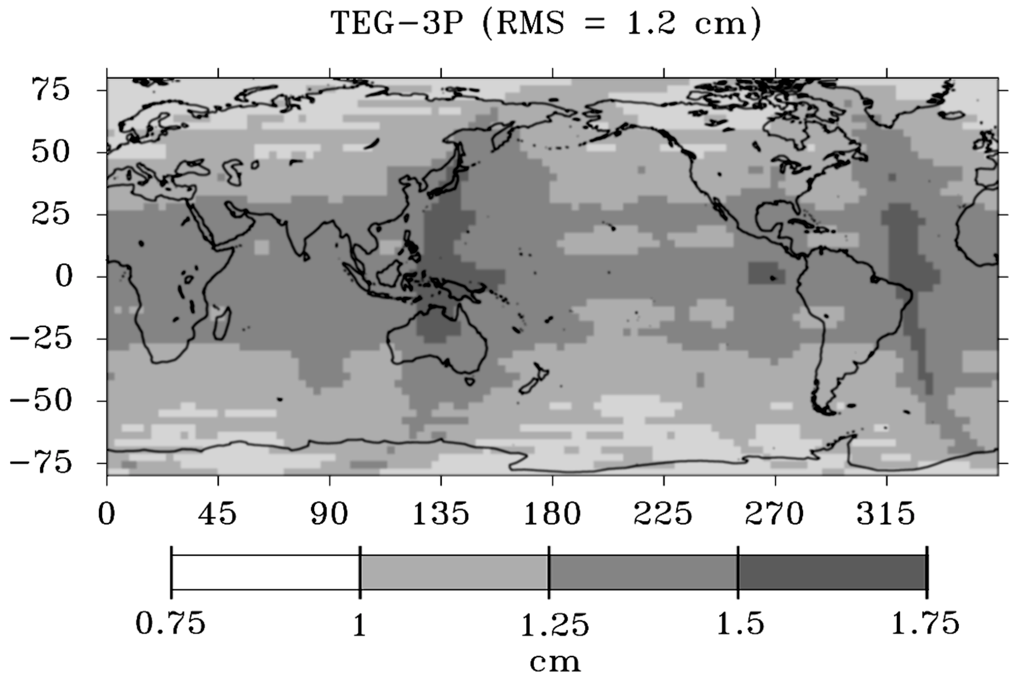

Figure 2. Geographically correlated orbit error for ERS-1 predicted by the TEG-3P covariance.

Ephemeris Access

The CSR trajectories are distributed in a terrestrial reference frame, specifically the IERS Terrestrial Reference Frame (ITRF), including polar motion. Precise ERS ephemerides can be obtained from the CSR anonymous ftp node:

ftp://ftp.csr.utexas.edu/pub/ers1/

The current export ephemeris format is the CSR ASCII INTERCHANGE format. Time system, sampling rate, start & stop times, reference frame, and ellipsoid parameters are contained within the single line text header of each ephemeris file. The ERS-1 ephemerides are divided into daily ephemerides, each having a unique Modified Julian Day (MJD) suffix. These daily ephemerides are available in tar archives grouped by year (i.e. ers1.1993.tar). Files within the tar archives are also UNIX compressed.

To decompress a tar archive (*.tar), use the UNIX command:

% tar -xf [archive_name]

To decompress compressed files (*.Z), use the UNIX command:

% uncompress *.Z

The *.daily directories contain hundreds of individual MJD files. It is recommended that the tar archives be downloaded unless the trajectory information for only a few individual days is required (specific SAR images, for example) or the network connection cannot complete a sustained download (each tar file is ~85 megabytes). The MJD filename nomenclature is: ers1.#####.Z, where ##### is the MJD number. The following dates indicate the various phases for the ERS-1 mission adopted at UT/CSR:

ERS1 PHASE A	MJD: 48462 - 48618
ERS1 PHASE B	MJD: 48622 – 48707
ERS1 PHASE C	MJD: 48725 - 49344
ERS1 PHASE D	MJD: 49344 - 49452
ERS1 PHASE E&F	MJD: 49452 - 49797
ERS1 PHASE G	MJD: 49797 - 50269

For reference, the Modified Julian Dates for each year are:

1991: MJD: 48257 - 48621
1992: MJD: 48622 - 48987
1993: MJD: 48988 - 49352
1994: MJD: 49353 - 49717
1995: MJD: 49718 - 50082
1996: MJD: 50083 - 50448
1997: MJD: 50449 - 50813
1998: MJD: 50814 - 51178

Interpolation Software

The sampling of the ERS-1 ephemerides is 30 seconds and the time system is UTC. The position and velocity are given in the Earth-fixed rotating reference frame (i.e. Earth rotation and polar motion applied). An interpolation scheme is necessary to provide the satellite state at the actual times of the altimeter data. An easy-to-use interpolation subroutine has been developed that interpolates an ERS-1 orbit with a 30 second sampling to a fraction of a millimeter maximum error (Seago, 1997).

The CSR ephemeris processing and interpolation software is available from:

ftp://ftp.csr.utexas.edu/pub/interp_bundle

The software is a complete bundle of source code and documentation, and is compatible with existing CSR ASCII Interchange ephemerides. A copy of the README.FIRST file is attached in the Appendix 3, which provides further documentation about using the interpolation code and verifying the execution using sample ephemerides.

Acknowledgements

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This document, the accompanying software, and the CSR precise ephemerides are distributed as a set. Original source code and ephemerides remain the property of the University of Texas at Austin / Center for Space Research and their respective authors, and may be distributed among those agencies and individuals having access privileges to CSR ephemerides. No individual, employee, or agency may otherwise release or redistribute this material without the permission of the Center for Space Research. All publications or research deriving results from the use of these ephemerides and/or software should appropriately credit the University of Texas Center for Space Research.

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APPENDIX 1

ERS-1 Altimeter Data Description

The ERS-1 GDRs are distributed by CERSAT, and called OPR (Ocean PRoduct) altimeter data. Currently, the data exists in two different OPR format versions: version 3 [CERSAT, 1995] and version 6 [CERSAT, 1996b]. However, most of the altimeter corrections are replaced for use at the Center for Space Research (CSR) and for the ERS-1 JPL CDROM [Berwin et al., 1996], yielding greater continuity between the two datasets. The two most important measurements that are not perfectly consistent between the two OPR versions are the measured wet troposphere correction and the altimeter measurement itself. The different OPR versions of the altimeter ranges essentially only introduce a bias, which is estimated. Several analyses focus on the wet troposphere correction [c.f. Bernard, 1993; Stum, 1994; Eymard et al., 1995; Urban et al., 1997; Kruizinga, 1997; Stum et al., 1998; Urban et al., 1999]. The ERS-1 mission uses three different ground-track repeats of 3, 35, and 168 days, broken into seven distinct mission phases labeled chronologically A through G. Phases A, B and D are 3-day repeats, phases C and G are 35-day repeats, and phases E and F are 168-day repeats. The following table lists the original OPR and new corrections applied to the altimeter data for all seven ERS-1 mission phases (Urban, 1999). All corrections are rounded to the nearest mm before being applied to the altimeter data.

ERS-1 Original OPR and Revised Altimeter Corrections

Correction	GDR source	Revised source
wet troposphere	EMR1 measurement or FNOC model	EMR1 measurement or ECMWF model [ECMWF, 1995]
dry troposphere	FNOC model	ECMWF model [ECMWF, 1995]
ionosphere	Bent model [Llewellyn & Bent, 1973; Jones & Gallet, 1960]	IRI-95 model [Bilitza, 1990, 1996]
ocean tide	[LePrevost, 1994]	CSR3.0 [Eanes & Bettadpur, 1995]
solid earth tide	[Cartwright, 1971, 1973]	T/P model [Cartwright, 1971, 1973]
pole tide	none	T/P model [Wahr, 1985]
sea state bias	[Gaspar & Ogor, 1994]	[Gapar & Ogor, 1996]
other	none	USO [Loial, 1999a] and SPTR [Loial, 1999b]
orbit	DPAF precision orbit	CSR TEG-3P [Bordi, 1999]

ERS-1 Wet and Dry Troposphere Corrections

The wet troposphere correction that is calculated from the ERS-1 Microwave Radiometer (ERM1) is incorrect on the OPR version 3 CDROMS. For phases A through F, the following correction must be made to the wet troposphere correction [Stum et al., 1998]:

$$wet_{CORR} = 0.803 * \{wet_{OPR} + 0.304 * (U-7)\} - 0.55$$

where wet_{OPR} is the incorrect OPR wet troposphere correction, U is wind speed in m/s, and wet_{CORR} is the fully-corrected wet troposphere correction. No correction is necessary for to the ERM1 wet troposphere correction for phase G (OPR version 6).

The ERS-1 model wet and dry troposphere corrections on the OPR CDROMs use the FNOC model, derived from European Centre for Medium-Range Weather Forecasts (ECMWF) model outputs. The new model troposphere corrections applied to the altimeter data use the original ECMWF model data [ECMWF, 1994]. The data originates in spherical harmonic form, incorporating 14 or 15 pressure levels, at four times per day. The ECMWF model data was carefully integrated by CSR into 6-hourly, 1 degree by 1 degree mean sea level grids, for application to the ERS-1 altimeter data. The main FORTRAN subroutine used for calculating the model troposphere correction is "atmcor", with the following header:

```
c          subroutine atmcor(mjd,rlat,rlon,dry,wet)
c
c      purpose: compute dry and wet tropospheric correction given
c               time,latitude and longitude at mean sea level
c
c      coded by: Gerard L.H. Kruizinga               07/22/94
c      modified: Gerard L.H. Kruizinga               02/10/95
c                    adapted for ECMWF, NMC or any other field
c
c
c      input:
c            mjd          modified julian date
c            rlat         latitude (degrees)
c            rlon         longitude (degrees)
c      output:
c            dry          dry tropospheric correction (mm)
c            wet          wet tropospheric correction (mm)
c
c      notes:
c           - this subroutine has been optimized for sequential times
c           - logical unit number 99 is used by this subroutine
```

ERS-1 Ionosphere Correction

The ERS-1 ionosphere correction on the CERSAT OPR CDROMs is the Bent model [Llewellyn & Bent, 1973; Jones & Gallet, 1960]. The revised ionosphere correction on the

JPL CDROMs is the IRI-95 model [Bilitza, 1996], based upon the International Reference Ionosphere [Bilitza, 1990]. The main FORTRAN subroutine for IRI-95 is "irit13" [Dieter Bilitza, personal communication, 1995], called as below:

```
call irit13(alati, alongi, iy, md, hour, hbeg, hend, tec, tecb, tect, error)
```

where the inputs are:

alati = latitude (North) of the subsatellite point (degrees) (real)
alongi = longitude (East) of the subsatellite point (degrees) (real)
iy = four digit year of observation (integer)
md = four digit month-day, computed as month*100 + day of month (integer)
hour = hours past midnight (real)
hbeg = beginning altitude for electron content integration (km) (real)
hend = ending altitude for electron content integration (km) (real)

and the outputs are:

tec = total electron content in m^(-2)
tecb = percentage of bottomside content
tect = percentage of topside content
error = flag indicating valid tec calculation (0) or invalid (1)

The "irit13" subroutine is called through the "iono_corr_iri95dec" subroutine, coded at CSR (by T. Urban, November 10, 1995). This subroutine is called as:

```
call iono_corr_iri95dec (dmjd, klat, klon, korbit, new_iono, tec, satid, error)
```

where the inputs are:

dmjd = modified Julian Date (= JD - 2400000.5) (double precision)
klat = latitude (North) of the subsatellite point (microdegrees) (integer)
klon = longitude (East) of the subsatellite point (microdegrees) (integer)
korbit = satellite altitude (mm) (integer)
satid = satellite identification number (integer)

and the outputs are:

new_iono = ionosphere correction to the altimeter range (negative) (mm)
tec = total electron content (m**-2) (real) = irit13 output
error = flag indicating valid tec calculation (0) or invalid (1) = irit13 output

Calculations performed in the "iono_corr_iri95dec" subroutine <u>before</u> calling the "irit13" subroutine are:

1. Conversion of time from MJD to "irit13" input format.
2. Conversion of klat, klon (integer, microdegrees) to alati, alongi (real, degrees).
3. Assignment of 100 (km, real) to hbeg (the lowest valid limit of irit13).
4. Conversion of korbit (integer, mm) to hend (real, km).

The calculation performed in the “iono_corr_iri95dec” subroutine after calling the “irit13” subroutine is the computation of the ionosphere correction (new_iono) from the formula [Bilitza, 1990]:

```
new_iono = -40.3e3 * tec / (freq**2)
```

where

freq = the frequency of the ERS-1 radar altimeter (Hz) = 13.8e9 Hz, from a lookup table of values using satid.

Solid Earth Tide Correction

The solid Earth tide on the OPR CDROMs is based on Cartwright & Ray [1971] and

Carwright & Edden [1973]. In order ensure that the exact T/P solid Earth tide model is applied, the tide is replaced using the FORTRAN subroutine “tidpot”. The header of this subroutine is as follows:

```
C      This subroutine is an implementation of the tide-generating
C      potential as given by Cartwright and Tayler (Geophys. J R. Astr
C      Soc, 1971, 23, 45-74) as corrected by Cartwright and Edden
C      (Geophys. J. R. Astr Soc., 1973, 33, 253-264).
C
C      HISTORY:
C
C      Changes for TOPEX/POSEIDON:
C      1.  Amplitudes (CS arrays) have been updated to 1990 era
C      per Woodworth.
C      2.  Amplitudes for K1 and its sidebands (CS elements 213-215)
C      have been scaled by the ratio between the K1 Love number (0.52)
C      and the overall second degree Love number (0.609), i.e. by 0.854.
C      When the potential is later multiplied by the overall Love number,
C      the result comes out correct (i.e. with correct K1 Love number).
C      3.  CS elements 20 and 21 have been swapped, as suggested by
C      Woodworth.
C      4.  Editorial changes--comments, spacing, etc. (JWB, 1992-Feb-20)
C      5.  Performance optimizations -- JWB, 1992-May-05
C      .      -- Use generic functions (e.g. COS instead of DCOS).
C      .      -- Use integer exponents.
C      .      -- Calculate coefficients first call only.
C      .      -- Pre-convert INTEGER K's to REAL X's.
C      .      -- Use single precision for quantities in loops
C      .      --   (about +/- .03 mm maximum error relative to original)
C      .      -- Delete MOD function inside loops.  (SIN and COS should
C      .      --   be ok without it).
C
C      Inputs:
C
C      DLAT - Latitude is positive north (degrees, DOUBLE PRECISION)
C      DLON - Longitude is positive east (degrees, DOUBLE PRECISION)
C      DMJD - Time given as MJD (MJ = JD-2400000.5);
C      +      MJD of midnight Jan 0-1,1900 is 15020.
```

```
C
C     VARY -- input <<<<
C     The first term in the second degree series is a zero frequency
C     (constant) term usually called the lunar and solar flattening
C     (it is multiplied by P20).  If this term is to be included, the
C     logical parameter 'VARY' should be set .TRUE.; if not, .FALSE.
C
C     Outputs:
C
C     V2, V3 - second and third degree potential values in MKS system.
C     DG     - gravity effect in milligals
C     V2LAT,V2LON,V3LAT,V3LON - partial of V2 and V3 wrt lat and long.
C
C     This subroutine was modified some time in the past to include
C     the earth tide response as a straight 16% increase in the
C     luni-solar gravity value. (1/6/86 - Alice Drew)
```

Once the tidal potential has been calculated, the "tidpot" subroutine calls the "sdp_g1062" subroutine, which has this header:

```
C     This subroutine implements algorithm G1062 - Solid Earth Tide -
C     by converting interfaces as required and calling the routine
C     TIDPOT to do the actual tide calculations.
C
C     CALL INPUTS --
C     Time_Tag  - SDS frame time tag in D.P. seconds past J2000
C     Latitude  - Latitude at which tides are to be calculated (D.P.)
C     Longitude - Longitude at which tides are to be calculated (D.P.)
c     dmjd      - mod. jul. date
C
C     CALL OUTPUTS --
C     Solid_Earth_Tide - Solid Earth tide height in mm (DOUBLE PREC.)
C
C     INPUT COMMONS --
C     None.
C
C     OUTPUT COMMONS --
C     None.
C
C     INPUT FILES --
C     None.
C
C     OUTPUT FILES --
C     None.
C
C     DEBUG FLAGS --
C     None. (in caller)
C
C     REFERENCES --
C     SDS FDD  (633-752)
C     SDPS SRD (633-751-21)
C     Sci. Algo. Spec. (633-708, Rev. A, Change 1, April 25, 1991)
C
C     HISTORY --
C     1992-FEB-20 -- JWB -- Original code. modified from EARTHTIDE
C     +                  --  supplied by B. Lambrigtsen
```

```
C
C     Copyright 1992, California Institute of Technology.
C     U.S. Government sponsorship under NASA contract NAS7-918
C     is acknowledged.
```

The original versions of these subroutines include a mix of real and double precision parameters. For implementation by CSR for ERS-1 processing, both codes were converted to use only double precision numbers. The latest reference for this solid Earth tide is McCarthy [1996].

Ocean Tide Correction

The ocean tide on the OPR CDROMs is based on LePrevost [1994]. For improvement, and for consistency with T/P, the OPR ocean tide is replaced with the CSR 3.0 model [Eanes & Bettadpur, 1995]. For further information about the model and the subroutines used for its implementation, see ftp.csr.utexas.edu:/pub/tide/README

Pole Tide Correction

The ERS-1 OPR CDROM data do not include the pole tide correction. The same pole tide that is used as for T/P is applied to ERS-1 data, using the FORTRAN "pole_tide" subroutine, coded at CSR (by G. Kruizinga, November 20, 1995). A correction to the x and y polar motion components was performed on August 6, 1996 (by T. Urban).

```
ccc Old incorrect values
c     data             xpbar,ypbar/0.294d0,.046d0/
ccc New values (corrected August 6, 1996)
      data             ypbar,xpbar/0.293d0,.042d0/
```

The original pole tide reference is Wahr [1985]. Details of the current standard can be found in McCarthy [1996].

Sea State Bias Correction

The ERS-1 OPR contains the outdated Sea State Bias (SSB) correction from Gaspar & Ogor [1994]. The SSB correction for ERS-1 is [Gaspar & Ogor, 1996]:

```
      SSB = SWH *(-0.047 - 0.0035*U + 0.00016*U**2)
```

where SWH is the significant wave height (in mm), and U is the wind speed (in m/s).

Additional Altimeter Corrections

Unlike other GDRs, the ERS OPR does not include all instrumental corrections. The Ultra-Stable Oscillator (USO) [Loial, 1999b] and Single Point Target Response (SPTR) [Loial, 1999a] corrections are applied externally, from tables of values found at the reference web pages. The USO correction table is linearly interpolated to the altimeter observation time. The

SPTR correction is non-continuous, and the correction is assumed constant between table values.

Estimated Biases for the ERS-1 Altimeter Data

In addition to updating the ERS-1 corrections to be more consistent (with itself and with T/P), biases in the data had to be estimated and removed in order to use the data for orbit determination. For example, the altimeter range bias between ERS-1 and T/P had to be removed from the dual-satellite crossovers. There was clear evidence of a bias in the time tag of the altimeter data that persisted throughout the ERS-1 mission, and a time bias has a significant effect on the crossover residuals if not removed. There also was evidence of a small but statistically significant bias in the correction for the sea-state or electromagnetic bias (EM bias).

These biases were estimated for each repeat cycle, but average values were determined for each phase. The small variations from cycle to cycle probably do not represent real variations but rather, uncertainty in the estimates. An average for each phase was considered likely to be a more accurate representation of the true bias for that interval of time. The following table lists the average values estimated for the ERS-1 altimeter data for each phase. The latest version of this table is maintained in the same directory as the orbit files.

Phase	Altimeter Bias (cm)	Time Tag Bias (ms)	EM Bias (% of SWH)
A	-44.2	1.94	0.28
B	-44.2	1.94	0.28
C	-44.2	1.66	0.25
D	-44.3	1.60	0.06
E & F	-43.6	1.52	0.09
G	-52.4	1.65	0.26

Notes:

1) The altimeter range bias is relative to a reference sea surface defined by T/P. The bias in the T/P altimeter is close to zero. A negative value indicates that the ERS-1 altimeter is measuring short. The uncertainty is estimated to be a few cm.
2) The time tag bias is in milliseconds. This value must be added to the altimeter time tag to arrive at the correct time tag, which would be used to call the orbit interpolator. The uncertainty is estimated to be approximately 0.2 ms.
3) The EM bias correction is estimated as a scale factor multiplied by the significant wave height (SWH). A positive value indicates that the magnitude of the EM bias correction must be increased, making the altimeter range shorter. The uncertainty is estimated to be roughly 0.2%.

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APPENDIX 2
D-PAF Orbits Description

3.2 Precise Orbit (ERS-1/2.ORB.PRC)

Definition

The precise orbits result from a data reduction process in which all available tracking data (SLR, radar altimeter crossovers, PRARE range and doppler data) and most accurate correction, transformation and dynamical models are taken into account and in which high level numerical procedures are applied. These orbits are "optimal" achievable representations of the real orbital motion under the circumstances of tracking situation and the "state of the art" model situation. The precise orbit product for the ERS satellites consists of the satellite ephemeris (position and velocity vectors) including time tag, given in a well defined reference frame, together with the nominal satellite attitude information and a radial orbit correction. The chosen reference systems for the satellite position and velocity representation are the Conventional Inertial System (CIS) and the Conventional Terrestrial System (CTS). The time frame used is the Terrestrial Dynamic Time (TDT). The precise orbit will be used for reduction of the radar altimeter measurements and the determination of geodetic/geophysical products.

Processing Scheme

Input:

- observations: Laser ranges, radar altimeter crossovers, PRARE range and doppler observations (ERS-2 only)
- Measurement model data: centre of mass correction, tropospheric corrections
- Reference frame model data: Earth rotation parameters, nutation model, station coordinates
- Dynamical model data: Earth gravity model, Earth and ocean tides, drag model, solar activity data, third body attractions

Algorithm:

Numerical integration of satellite's equation of motion and its variational equations, reduction of observations and iterative least squares adjustment.
Processing Parameters

- Orbital elements at initial epoch
- Global scaling factor for direct solar radiation pressure
- Daily or subdaily scaling factors for atmospheric drag
- Once per revolution empirical acceleration
- Global time bias (altimeter, PRARE)
- PRARE: station dependent range bias, tropospheric correction per pass

Constraints: To avoid any discontinuities of subsequent arcs over ocean, all orbits start and end over land except in case of manoeuvres.

Reduction of the ephemeris period by one day at beginning and end except in case of manoeuvres. The reduced subsequent subarcs end and start at the same epoch.

Computation of radial orbit corrections via global crossover analysis, merging of these corrections into the product file and concatenation of reduced subarcs to one monthly/35d-cycle product.

ASCII coded records
- Time system corrections to UTC
- Manoeuvre information
- Leap second information
- Reference frame identifier (CTS,CIS)
- Satellite ID (COSPAR number)
- Type of orbit (here: precise)
- Time tag in Julian Days since 2000.01.01 12 hours in TDT time scale
- Position of actual center of mass of ERS spacecraft
- Velocity of actual center of mass of ERS spacecraft
- Roll, pitch and yaw angles
- Flags for first ascending state above the equator and quality indicator (manoeuvre)
- Radial orbit correction
- Quality estimates

Product Specification

Spatial Coverage: global

Spatial Resolution: approximately 225 km

Time Coverage: app. 1 month or 1 35d-cycle, consisting of several continuous 5-7-day files

Time Resolution: 30 seconds

Reference System: CTS - Conventional Terrestial Reference System. Z-axis directed towards the **mean pole** as being derived from the BIH pole series (ERP(BIH)87C02) covering the period January 1980 - October 1986. X-axis fixed by allowing no net rotation about the Z-axis with respect to the initial coordinates (SSC(DGFII)91L01). Y-axis complete system to the right-handed.
The offsets to the IERS pole are 45 and 286 mas, i.e.
x_p^{IERS} - 0.045" = x_p^{DPAF} , y_p^{IERS} - 0.286" = y_p^{DPAF}

CIS - Conventional Inertial Reference System. This system is referred to the basic epoch 2000.01.01 12 hours designated J2000.0. The axes of the CIS are chosen in such a way, that at the basic epoch J2000.0 they coincide in optimal approximation with the mean equatorial frame defined by the mean celestial pole (Z-axis) and the mean vernal equinox (X-axis).

Coordinate System: geocentric cartesian coordinates

Time System: Terrestial Dynamic Time (TDT)

Constants, Models: according to ERS Standards

The main characteristics are

Gravity model	PGM-Model computed by D-PAF
Ocean tides	Schwiderski plus PGM-Model (D-PAF)
Station coordinates	PGM-Model (D-PAF)
Air drag	CIRA 86
Solar flux	final values
Geomagnetic ind.	final values
Surface forces	Macro-Model
Earth rotation	IERS Bulletin B (final values)
Nutation	IAU 1980 plus corrections (ERS-D-STD-31101)
Earth radiation	albedo and infrared
Earth tides	modified Wahr (Zhu et.al. 1991)

Times/Rates of Generation: D-PAF computes uninterrupted precise orbital subarcs of about 5 to 7 days worth of tracking data. All subarcs of one month/35d-cycle are compiled into one precise orbit product being available for users after a few months.

Product Presentation

Volume: app. 22.5 Mbyte per month/35d-cycle (uncompressed), 8 MByte (compressed)

Medium: CD-ROM, D-PAF FTP Server

Quality Assessment

The quality of the generated orbits is controlled formally and internally.

The formal quality control comprises procedures to check the correct format and to flag periods where the orbit is degraded by manoeuvres or platform anomalies.

Internal quality checks are performed by
- examining the fits of the laser ranges and the altimeter crossovers to the adjusted orbit
- comparing overlapping arc segments

Each product is complemented by records containing quality information like fit of the observations to the orbit, comparison of overlapping orbit segments, crossover rms (root mean square) before and after consideration of a radial orbit correction.

For the revision 1 orbits the radial accuracy is in the order of 12-15 cm, while the revision 2 provides about 8-10 cm radial accuracy.

PRC History

Date	PRC Period	Rev.	PGM Model	Remarks
01.01.92	Jul.91 - Mar.92	0	PGM009	observations: FR/NP SLR ranges only
20.07.93	Jul.91 - Dec.93	1	PGM035	observations: SLR+RA crossovers (QLOPR) improved Satellite Macro Model introduction of radial orbit correction (ROC) computed from QLOPR
24.01.94	Oct.-Dec.92, Jul.91-Mar.92, Aug.93 ff	1	PGM035	ROC flag introduced for no correction due to missing RA data, over land position, above threshold of 60cm Solving also for 1/rev empirical acceleration along-track
07.02.94	Sep.93, Nov.92	1	PGM035	ROC: first + last position over land not flagged "over land" anymore for interpolation reasons (only CIS states)
07.03.94	Oct.93 ff, Jul.91-Mar.92, Dec.92	1	PGM035	ROC: first + last position over land not flagged "over land" for CIS + CTS states
07.94	Jan.94 ff, Jul.91-Mar.92	1	PGM035	RA crossovers are now based on OPR01 data from F-PAF ROC is also computed from OPR01 data
21.03.95	-	-	-	Opening of D-PAF FTP Server for product distribution to PIs
01.04.95	-	-	-	Removal of CCT devices, switch to CD-ROM as distribution medium
Aug.95	Mar.24, 1995 ff	2	PGM055	improved gravity model, product presentation changed to 35d cycle, 1/rev empirical acceleration per day along-track and cross-track
-	E2: Dec.12, 95 ff	2	PGM055	Operational use of PRARE data (Rev.4)
-	E2: Dec.22, 95 ff	2	PGM055	Routine usage of RA crossover data terminated
-	E1: Jan.19, 96 ff, before April 95	2	PGM055	Crossover time bias solved-for
-	E1: Feb.26, 96ff, before April 95, E2: Dec.01, 95 ff	2	PGM055	Use of improved OPR01 (time bias, SPTR, USO drift)
-	E1: Jun.06-Jul.26, 96	2	PGM055	Products generated from SLR data only

The different PGM models can be characterized as follows:

Model	Degree	Basic Model	Differences
PGM009	63	GRIM4-S2	+ first preliminary ERS-1 SLR data
PGM035	66	GRIM4-S3	Spot/Doris data replaced + Topex SLR/Doris data (Oct.-Dec.92) + ERS-1 SLR data (Apr.-Jul.92)
PGM055	69	GRIM4-S4	+ ERS-1 SLR/Crossover data (35d, 168d data)

APPENDIX 3

EXPORT DOCUMENTATION FOR
MODULE INTERPOLATING PRECISE SATELLITE EPHEMERIDES (MIPSE)
University of Texas at Austin / Center for Space Research

DISTRIBUTION, RESTRICTIONS, & CONDITIONS

This document, the accompanying software, and the CSR precise ephemerides are distributed as a set. Original source code and ephemerides remain the property of the University of Texas at Austin / Center for Space Research and their respective authors, and may be distributed among those agencies and individuals having access privileges to CSR ephemerides. No individual, employee, or agency may otherwise release or redistribute this material without the permission of the Center for Space Research. All publications or research deriving results from the use of these ephemerides and/or software should appropriately credit the Center for Space Research.

OVERVIEW

CSR distributes precise satellite ephemerides in several formats. Currently the general format supported by CSR for export is the CSR ASCII INTERCHANGE format; other formats are considered obsolescent.

CSR provides FORTRAN source code to process these CSR ephemerides. This generic interpolation module, called MIPSE (Module Interpolating Precise Satellite Ephemerides), handles both the older CSR GROUNDTRACK format and the newer CSR ASCII INTERCHANGE format. MIPSE can process ephemeris files of arbitrary length (limited only by machine memory) and is not limited to a specific ephemeris sampling rate or step size. A third format, the CSR BINARY format, is recognized by MIPSE but is not generally available for distribution outside CSR.

CSR has added a new file structure to its ftp node. Ephemerides are now sub-divided into daily files, numbered according to Modified Julian Date (MJD). A simplified software interface has been established to assist in processing these specially sized files, called MIPSE_MJD, which is a convenient driver for the already established MIPSE module. Users processing MJD structured ephemerides are encouraged to use the MIPSE_MJD driver in lieu of MIPSE directly. Other (non-daily) file structures may still use the MIPSE module directly.

EPHEMERIS ACCESS

The CSR precise ephemerides are available via anonymous FTP from the CSR FTP node:

ftp://ftp.csr.utexas.edu/pub/

Individually numbered MJD ephemeris files are divided by annual subdirectory. Files having been UNIX compressed may be decompressed using the 'uncompress' command on UNIX platforms, or personal computer applications such as 'UnZip' or 'Stuffit'.

Users needing trajectories spanning more than a few isolated days may download tar archives of entire annual periods. These tar archives may be unarchived using the UNIX command: tar -xf 'archive_name', or a personal computer application that emulates tar archiving. The individual files that have been archived must also be decompressed.

SOFTWARE ACCESS

The CSR ephemeris interpolation bundle is available via anonymous FTP from the CSR FTP node:

ftp://ftp.csr.utexas.edu/pub/interp_bundle/

Documentation and source code is provided in the form of a tar archive.

Documents include the following:

```
---------
   mipse.doc - documentation for the CSR interpolation package.
  makcsr.doc - documentation for the CSR Ephemeris Generator.
 formats.doc - documentation for CSR ephemeris formats (optional).
```

FORTRAN Source:

```
--------------
     mipse.f - FORTRAN source code containing the CSR interpolation
               module MIPSE and MIPSE_MJD plus dependents.
    makcsr.f - FORTRAN source code containing the CSR Ephemeris
               Generator plus dependents (minus mipse.f source), a
               sample driver for the MIPSE module.
       a2b.f - a FORTRAN program that converts the CSR ASCII INTERCHANGE
               format to a CSR BINARY format ephemeris.
```

Test Ephemerides:

```
----------------
astest.30sec.49331:  demo  input CSR ASCII ephemeris for MIPSE_MJD
astest.10sec.49331:  demo output CSR ASCII ephemeris for MIPSE_MJD
astrue.10sec.49331:  truth ephemeris integrated via UTOPIA POD software

gttest.30sec.49331:  demo  input CSR ASCII ephemeris for MIPSE_MJD
gttest.10sec.49331:  demo output CSR ASCII ephemeris for MIPSE_MJD
gttrue.10sec.49331:  truth ephemeris integrated via UTOPIA POD software
```

WHAT'S NEXT?

After successfully obtaining the desired ephemerides, software, and documentation, please read the file 'mipse.doc' and refer to the comments within the source code as necessary.

08/18/1997 JHS
