The Orbit Control of ERS-1 and ERS-2 for a Very Accurate Tandem Configuration

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Abstract

The concept of “interferometric baseline” for stereoscopic radar imaging is explained. It is demonstrated that the interferometric baselines for the images made with ERS-1 and ERS-2 have been maintained in the desired range 300 ± 50 m. It is also shown that the altitudes at which the matching images are made only deviate by 2-3 meters, i.e. the only difference for the imaging geometry is this desired non-zero baseline.

Key words: Satellite Configuration, Tandem Mission

Introduction

ERS-1 was launched the 17th of July 1991 by Ariane V44 and ERS-2 the 21th of April 1995 by Ariane V72. The spacecraft are orbiting the Earth in near-circular, near-polar, sun-synchronous orbits with a 35 days / 501 orbits repeat cycle and with the Local Time of Descending Node equal to 10:30. This means that the spacecraft make 14 11/35 orbits in one day and that the altitude is about 800 km. ERS-1 is leading ERS-2 with 11/35 of an orbit to obtain that ERS-2 has exactly the same ground track as ERS-1 had one day earlier. This is the meaning of the concept “tandem configuration”. The basic accuracy requirement for the orbital repeats is that a control dead-band for the ground track of ± 1 km shall be respected.

The ERS spacecraft carry an Active Microwave Instrument (AMI) with the modes

- Synthetic Aperture Radar (SAR) Image Mode
- Wave Mode
- Wind scatterometer Mode

In addition the spacecraft are equipped with a Radar Altimeter and an Along-Track Scanning Radiometer and Microwave Sounder (ATSR)

In image mode the SAR obtains strips of high-resolution imagery 100 km in width to the right of the satellite track. The 10 m long antenna, aligned parallel to the flight track, directs a narrow radar beam onto the Earth’s surface over the swath. Imagery is built up from the time delay and the strength of the return signals, which depend primarily on the roughness and dielectric properties of the surface and the range to the satellite.

For ERS the method of SAR interferometry has been developed. This technique is based on the stereoscopic effect that is obtained by matching two SAR images obtained from two slightly different orbits. This off-set creates an “interferometric baseline” as discussed in more detail below. The optimal “interferometric baseline” is 300 ± 50 m.

It has indeed been possible to keep the baseline within these bounds but to achieve this the accuracies intrisic to the system had to be stretching to the very limit.

The interferometric baseline

The actual geometry for the SAR imaging at the equator crossing that for ERS-1 took place 1998/12/23 at 21:35 UTC and for ERS-2 one day and 9.35 seconds later is displayed in figure 1.

The direction of view of the figure is the direction of flight relative to the Earth, i.e. relative to a coordinate system rotating with the Earth[1]. The vertical line is the local vertical to the point at the intersection between longitude 13.784587 deg E and the equator. The points are the crossings of the spacecraft orbits of the plane of the paper. The direction of view of the side-looking radars is making an angle of 20.3 deg to the vertical and the interferometric baseline is the displacement of the orbits orthogonal to this direction of view. The altitude of ERS-1 at this point as determined from the tracking is 787.300 km and the altitude of ERS-2 at corresponding point is 787.303 km, i.e. ERS-2 is 3 meters higher than ERS-1. At this occasion the interferometric baseline was then 345 m, i.e. close to the upper limit of the optimal interval 300 ± 50 m.

At the equator the rotation of the Earth corresponds to a velocity on the surface of the Earth of 465 m/s. The effect of an along track deviation corresponding to 0.01 seconds of flight is therefore 465 * 0.01 = 4.7 m As the orbital velocity of the spacecraft is about 7460 m/s the along-track position of the spacecraft must be controlled to an accuracy of 7460 * 0.01 = 75 m to get the desired interferometric baseline to an accuracy of 5 m. If this high accuracy of along-track control is achieved and also the altitudes for the two overflights are equal a geometry as displayed in figure 1 is obtained. The situation 25 minutes later at the time of over-flight of the point with geographical coordinates 86.024258 W 81.479744 N is displayed in figure 4. At this time the spacecraft are heading straight westward. The inertial velocity of the surface of the Earth below the spacecraft is low (close to the North Pole) and directed opposite to the orbital velocity of the spacecraft. The interferometric base line is therefore entirely a function of the difference in orbital inclination between ERS-1 and ERS-2. The osculating inclination of ERS-1 on 1998/12/23 at 21:59:59.891 was 98.55788 deg and the osculating inclination of ERS-2 on 1998/12/24 at 22:00:09.245 was 98.55769 deg. The baseline of 18 m at this point corresponds to this difference in inclination. The altitude of ERS-1 is determined to be 796.765 km and the altitude of ERS-2 to be 796.762 km, i.e. the difference in altitude is again 3 m but here ERS-2 is lower than ERS-1.

1. The plane is vertical, i.e. it is in fact orthogonal to the **horizontal** component of this relative velocity.

The interferometric baselines at 2 intermediate points of the orbit are displayed in figures 2 and 3. Over latitude 30 deg North the interferometric baseline is still in the optimal range (290 m) but at 60 deg North it is below this range (154 m). On the following South bound leg the interferometric baselines increase again to be 181 m at 60 deg north and 305 m at 30 deg North (figures 5 and 6).

The reason why (about) the same baseline is obtained for the north-bound and the south-bound passages of a given latitude is that ERS-1 and ERS-2 have almost exactly the same inclinations. For the points of figures 1-6 the following table gives the osculating inclinations in degrees:

Table 1:

Figure	ERS-1	ERS-2
1	98.54673	98.54654
2	98.54965	98.54946
3	98.55530	98.55512
4	98.55788	98.55769
5	98.55535	98.55517
6	98.54985	98.54966

It can be seen that the osculating inclination varies over an interval of ± 0.006 deg over these 6 points while the difference between ERS-1 and ERS-2 at corresponding points deviate with only 0.0002 deg, the inclination of ERS-1 being larger than the inclination of ERS-2.

As it is desirable to get optimal interferometric baselines both for the north-bound and the south-bound passes of a given SAR ground station the intention is to keep the orbital inclinations of ERS-1 and ERS-2 as equal as possible.

The Moon induces periodic perturbations of the inclination with a period of half a month. As the orbits of ERS-1 and ERS-2 are compared with one day shift this effect of the Moon gravitation is also shifted one day. Because of this phase difference the best that can be obtained is that the mean inclinations of ERS-1 and ERS-2 (mean over one orbit) will alternately be somewhat larger than the other, the period of this variation being half a month. The amplitude of this variation in inclination difference induced by the Moon is about 0.0003 deg corresponding to up to 30 m interferometric baseline at the northern and southern extremes. For this particular orbit the difference in mean inclination was 0.0002 deg. The consequence of this difference is that the baseline of figure 5 is slightly larger than the baseline of figure 3 and that the baseline of figure 6 is slightly larger than the baseline of figure 2. For the orbits for which the mean inclination for ERS-2 is larger than the mean inclination for ERS-1 the baselines at the north-bound legs are instead slightly larger than those on the south-bound leg.

The reference orbit

At all times and all phases of the mission the spacecraft shall follow the same trajectory relative to the Earth (i.e. relative to an Earth fixed rotating coordinate system). One way to achieve this is to prescribe a certain ground track **and** an altitude profile for the spacecraft to follow. For ERS such a reference ground track has been defined, the actual ground-track shall be kept within a control-deadband of ± 1 km around this reference ground track. For the altitude variations there is no such explicit control deadband but the requirement of flying a “frozen” absolutely Earth synchronous orbit automatically results in that the altitudes will vary with at most a few meters between the different over-flights of a point on the reference ground track.

The forces that significantly influence the orbit are:

- The Earth gravitation
- The Moon gravitation
- The Sun gravitation
- The Solar radiation pressure
- The air drag

The reference orbit for the ERS missions has been defined as the theoretical reference orbit defined as follows:

- The rotational axis of the Earth is assumed to be fixed in inertial space (no precession/nutation).
- The Earth is assumed to be rotating around the axis defined by the poles of the longitude/latitude system (no polar motion).
- The rotation phase of the Earth is assumed to be as given by Newcomb’s formula using uniform UTC time (no UTC/UT1 correction).
- The gravitational forces of Sun/Moon are assumed to be zero.
- The solar radiation pressure is assumed to be zero.
- The air drag is assumed to be zero.

This means that the theoretical reference orbit corresponds to an orbit affected only by the gravitational force (JGM3 truncated to 36 zonal and 36 tesseral terms) from a uniformly rotating Earth.

The theoretical reference orbit is then the completely periodic orbit (completely periodic relative an Earth-fixed coordinate system, period 35 days) that according to the theory of ref 1 exist under these assumptions.

The reference ground track is the ground track for this reference orbit. The reference altitude for a point on this ground track is the altitude of this reference orbit. Six such positions corresponding to figures 1-6 are:

Table 2:

Longitude	Latitude	Altitude
13.784587	0.000000	787.173
6.722299	30.000000	787.550
-5.480901	60.000000	793.608
-86.024258	81.479744	796.720
-159.505815	60.000000	793.512

Table 2:

Longitude	Latitude	Altitude
-171.709097	30.000000	787.392

The reference orbit passing exactly over these points at these altitudes is indicated with the small circles on the vertical line.

By following the local verticals through the actual crossings of these vertical reference planes (the filled circles in fig 1-6) the off-sets between the nominal ground track corresponding to this reference orbit and the ground track of the actual orbit can be determined. These off-sets as functions of time for ERS-1 and ERS-2 from 98/11/21 00:00:00 to 98/12/26 00:00:00 are shown in figures 7 and 8. The following phenomena are clearly visible from these plots:

- The off-sets at the equator form a curve of approximately parabolic shape due to the air drag
- The off-sets close to the pole are steadily increasing (from negative towards positive). This is due to the solar gravitation
- On top of the steady increase of the off-sets close to the pole there is a periodic variation with a period of half a month. This is due to the lunar gravitation

The following manoeuvres were made in this time period:

ERS-1

Table 3:

Day	Size	Type
0.24	1.983 m/s	out-of-plane
3.09	6.8 mm/s	in-plane
19.18	30.2 mm/s	in-plane

ERS-2

Table 4:

Day	Size	Type
1.23	1.991 m/s	out-of-plane
1.79	8.8 mm/s	in-plane
6.05	4.5 mm/s	in-plane
20.18	26.4 mm/s	in-plane

The manoeuvres made from day 0 to day 6.05, i.e. from 1998/11/21 0:00 Z to 1998/11/27 1:13 Z were to compensate for the in-plane effects of the out-of-plane manoeuvres and also for an attitude anomaly causing attitude control thrust. But after 1998/11/27 1:13 Z no special configuration trim manoeuvres were necessary, it was enough to maintain the configuration with the air drag compensation manoeuvres executed for ERS-1 on 1998/12/10 at 4:26 Z (day 19.18) and for ERS-2 on 1998/12/11 at 4:32 Z (day 20.18) that would have been made also without configuration control.

By simply subtracting the off-sets of ERS-1 plotted in figure 7 from the off-sets of ERS-2 plotted in figure 8 the plot of figure 9 is constructed. The lunar gravitational perturbations with a period of half a month can be seen in this plot. This causes a certain unsymmetry between the north bound and the south bound passes. It can be seen that the orbital periods are almost perfectly synchronized as the ground track off-set between ERS-1 and ERS-2 at the equator passages is between 290 m and 350 m from day 6 to the end of the time interval at day 35. In the time period from day 6 to day 19 it can even be seen that ERS-1 is slightly more sensitive to air drag than ERS-2 because of its somewhat lower mass (2297 kg against 2465 kg).

Accuracies required

The factors influencing the accuracy with which orbit control manoeuvres can be executed are

- the accuracy of the determined orbit
- the accuracy of the orbit prediction
- the accuracy of the manoeuvre implementation

With S-band tracking from the ground station in Kiruna (Sweden) and “state-of-the-art” orbit determination software the orbit is determined to an accuracy of about 1 m, the altitude being accurate to a few decimeter. Detailed data on this can be found in ref 2.

The accuracy of the orbit prediction (assuming a perfectly known initial orbit) is limited by the accuracy with which the air drag can be predicted. But for the maintenance of an accurate tandem configuration it is the difference in air-drag between ERS-1 and ERS-2 that matters. Only when a change in solar activities causes a **change** in air drag will the constellation and the interferometric baseline be affected because of the one day shift between the matching images of ERS-1 and ERS-2.

The accuracy with which the desired orbit manoeuvres can be implemented is limited by the manoeuvre dispersion **and** the granulation due to the use of an integer number of fixed length thrust pulses. The “Fine Control Mode” manoeuvres for ERS are made by firing an integer number of 0.125 second pulses with two hydrazine thrusters that with full tank pressure (blow-down system) deliver a force of about 15 Newton. These thrusters give about opposite torques to the spacecraft and as the net torque must be as close to zero as possible the granulation will be two pulses. With a mass of about 2500 kg this means 2 * 0.125 *15 / 2500 m/s = 1.5 mm/s. With the present tank pressure the granulation is about 1 mm/s. Typical manoeuvres for the compensation of the air drag are in the order of 10 - 20 mm/s. With a typical dispersion of say 2-3% the dispersion is of about the same order as the granulation. Fine configuration trim manoeuvres are typically made with 1 + 1 pulses or 2 + 2 pulses in which case the dispersion is negligible compared with the granulation effects. An along-track delta-V of 0.5 mm/s, the maximal granulation error, results in a change in the orbital period of 0.017 seconds and already after 6 revolutions (10 hours) the along track effect is 0.1 seconds which at the equator shifts the ground track with 465 * 0.1 m = 47 m (the Earth rotation results in a velocity of the Earth surface of 465 m/s at the equator). Only by carefully planning the operations taking this granulation into account has it been possible to maintain an interferometric baseline that almost all the time has been in the interval 300 ± 50 m in the latitude band of interest. To have a situation as demonstrated in the plot of figure 9 the orbital periods must be equal with an accuracy considerably better than 0.001 second.

Conclusions

With S-band tracking from the ground station in Kiruna (Sweden), “state-of-the-art” orbit determination software and by carefully planning the operations to reduce the “granulation error” resulting from the use of an integer number of fixed length pulses for orbit manoeuvres it has been possible to maintain an interferometric baseline that almost all the time has been in the interval 300 ± 50 m in the latitude band of interest. The time between the “configuration trim manoeuvres” has always been over a week, in many cases even several weeks.

The difference in altitude between ERS-1 and ERS-2 for these matching points are typically in the order of 2-3 meters.

References

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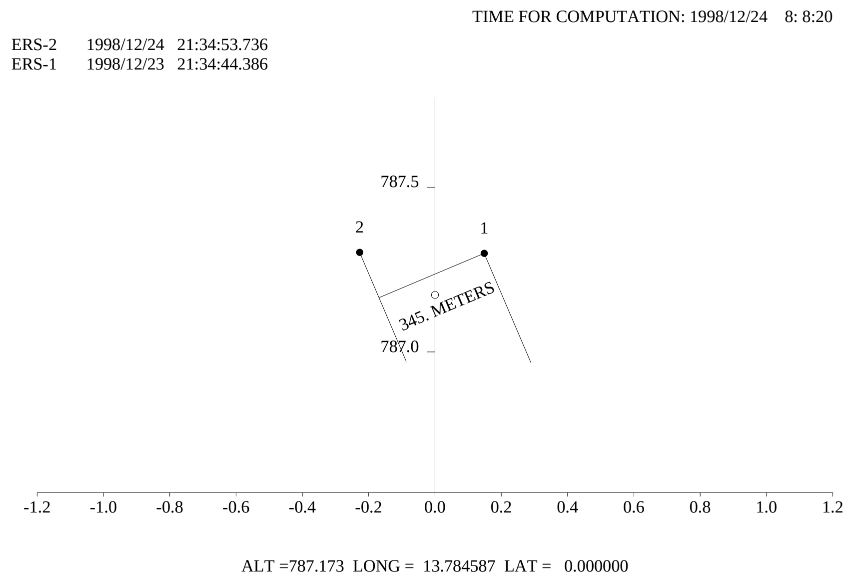

Fig 1: Crossings of the vertical plane defined by a reference point at the equator

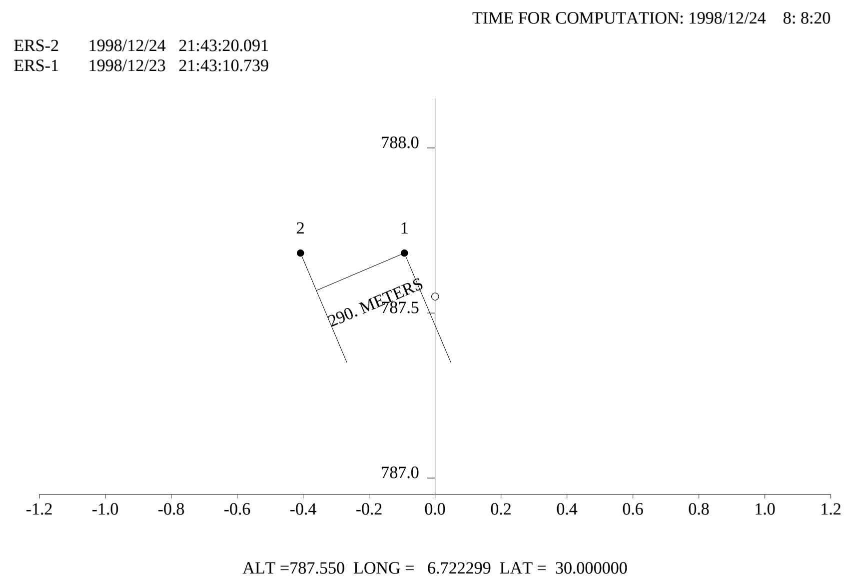

Fig 2: Crossings of the vertical plane defined by a reference point at 30 deg North

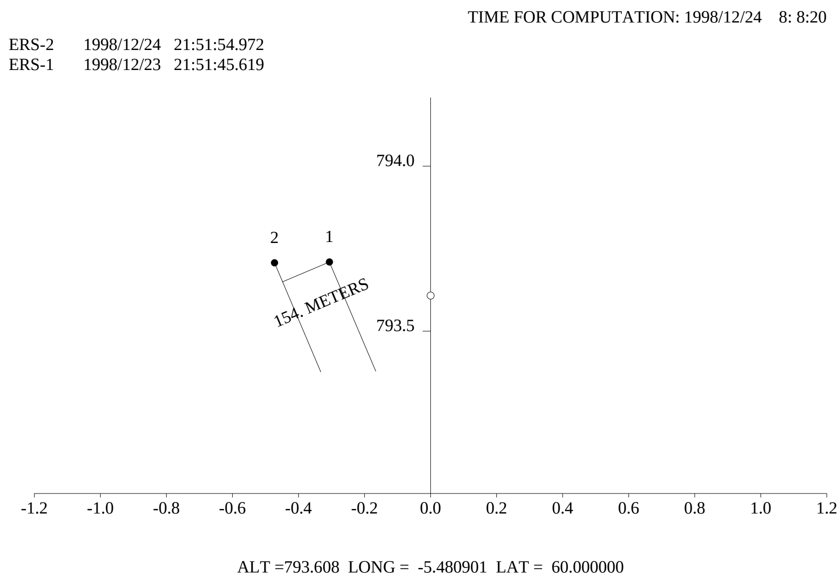

Fig 3: Crossings of the vertical plane defined by a reference point at 60 deg North

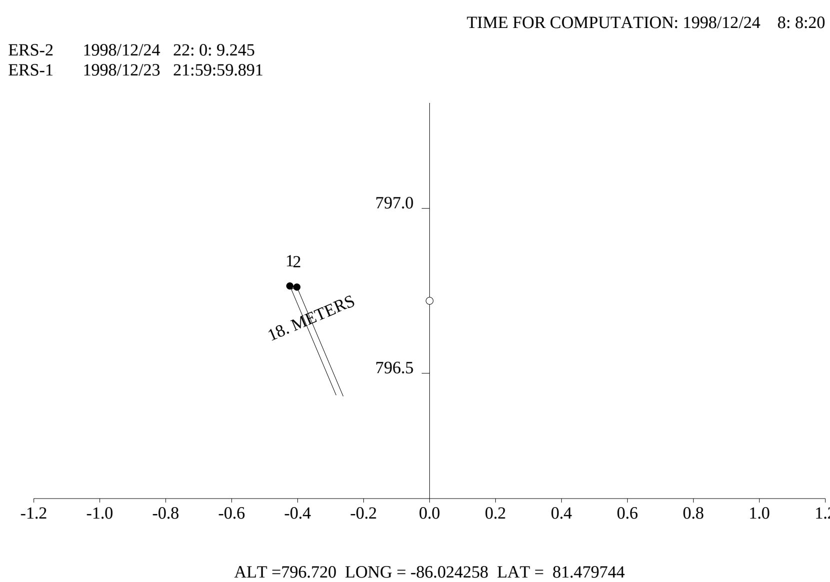

Fig 4: Crossings of the vertical plane defined by a reference point close to North Pole

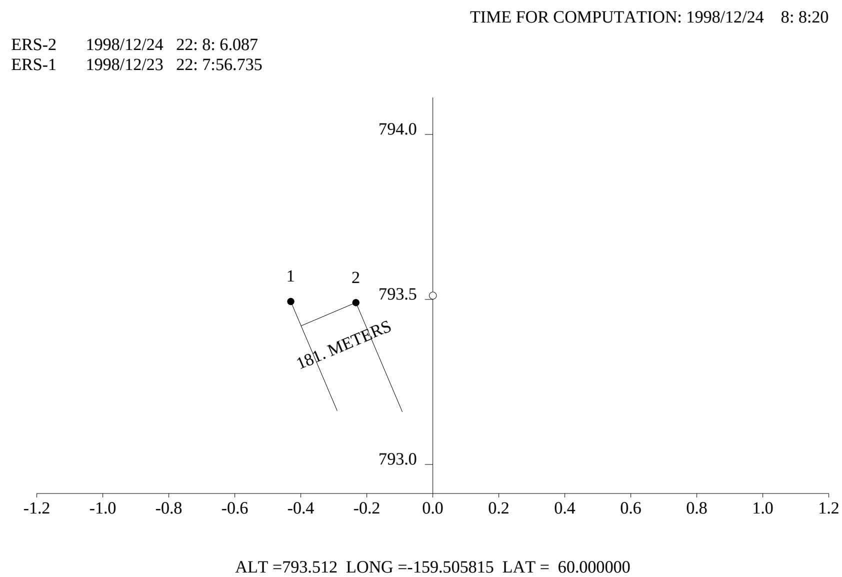

Fig 5: Crossings of the vertical plane defined by a reference point at 60 deg North

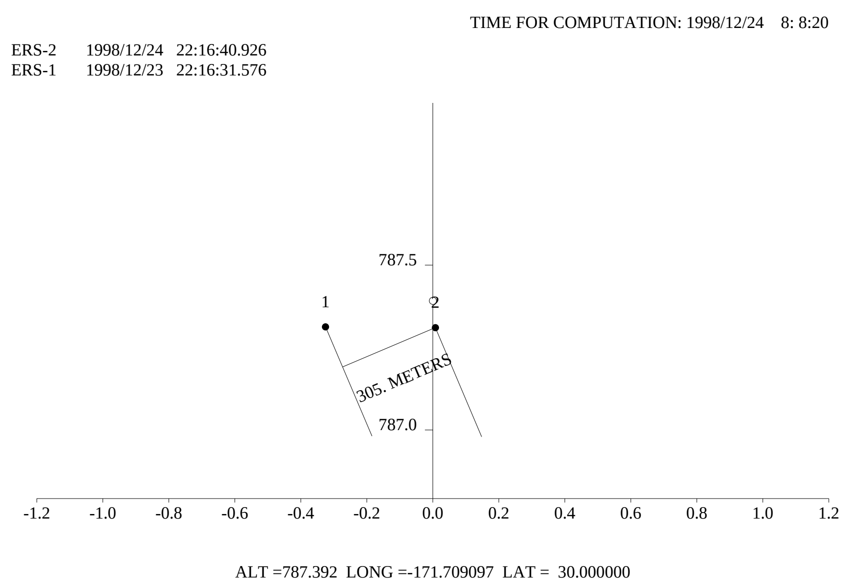

Fig 6: Crossings of the vertical plane defined by a reference point at 30 deg North

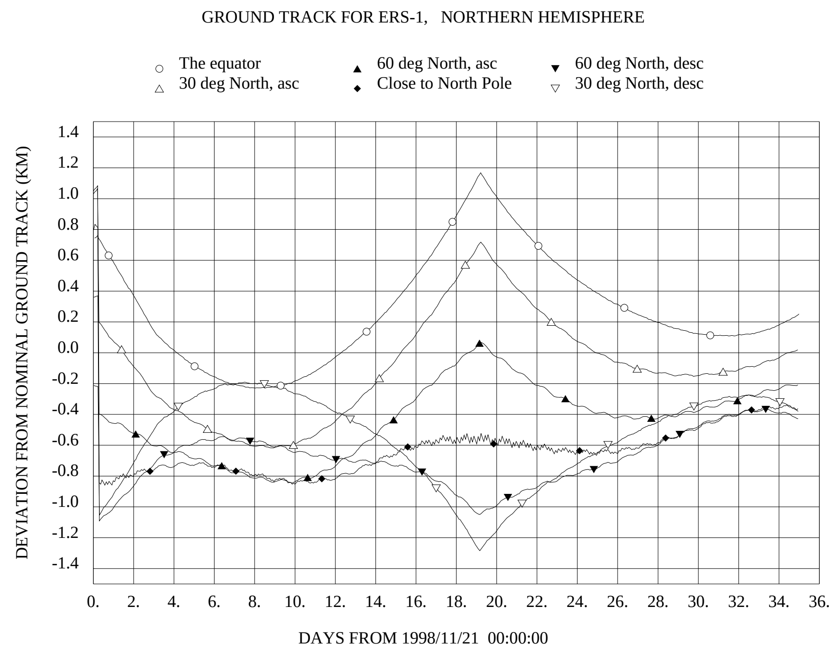

Fig 7: Deviation from the reference ground-track for ERS-1

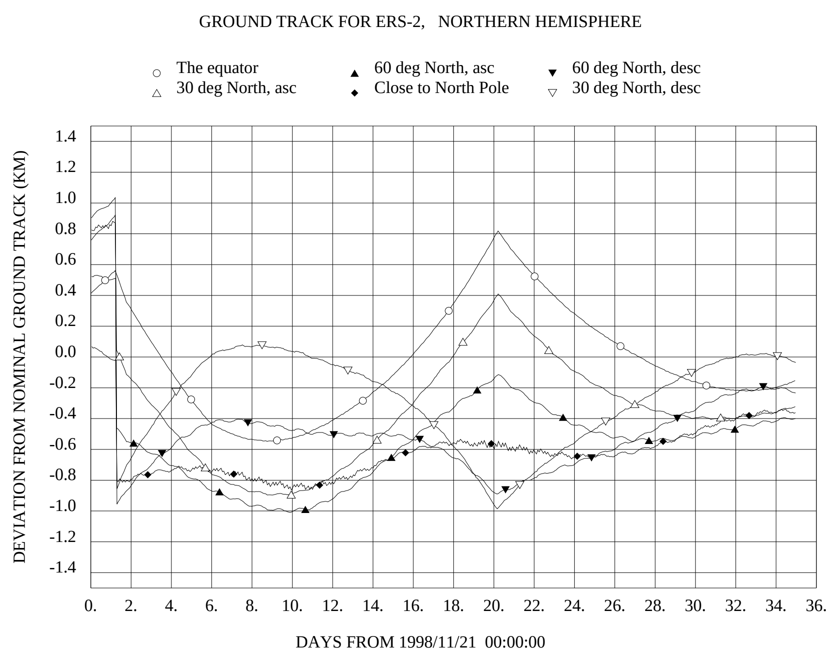

Fig 8: Deviation from the reference ground-track for ERS-2

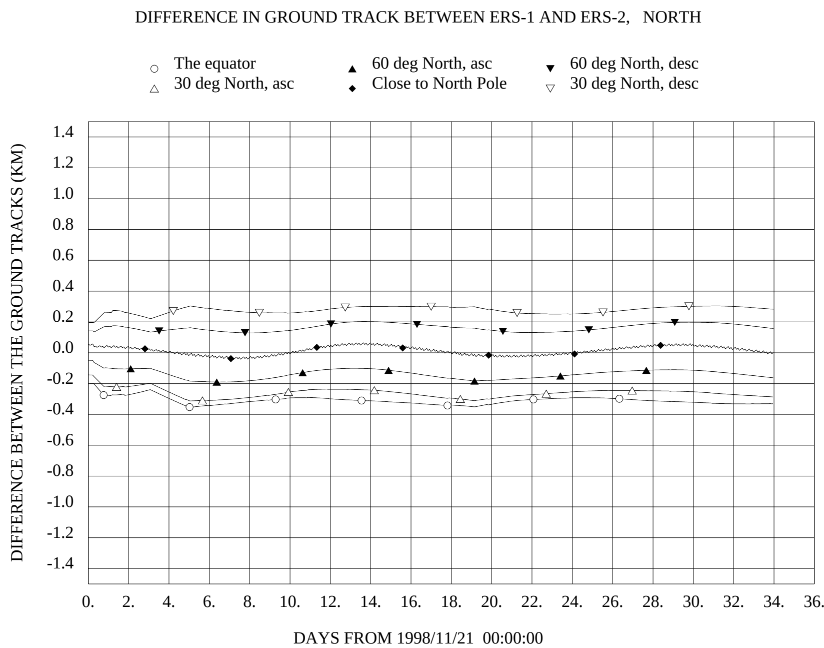

Fig 9: Difference in deviation from the reference ground-track between ERS-1 and ERS-2