Memo 2. Analysis of the MER-B VLBA Observations

Draft: January 5, 2005

ABSTRACT

The interferometric technique of VLBA phase referencing was used to determine the relative angular position of the Mars Exploration Rover (MER-B) Spacecraft with respect to nearby quasars. We analyzed three four-hour sessions on Jan 19, 21 and 23, 2004 in order to determine the accuracy and the feasibility of this technique. This report summarizes the VLBA observations and reductions, the incorporation of these data within the Orbit Determination Program, and the comparison of the VLBA and DSN ΔDOR results. The pathway from VLBA observations to Navigation use of the data is well-defined. The analysis shows that the 3-σ internal e/w accuracy of the VLBA observations, when compared with the accurate spacecraft orbit, was 1.0 nrad. This accuracy is about two times better than that from the DSN observations. Extension of the VLBA observations to 32 GHz will provide similar or better positional accuracy. The main limitation in obtaining absolute positions is associated with tropospheric refraction errors and the 1.0 nrad uncertainty of quasar positions, hence these contributions must be decreased in order to obtain more accurate positions in the future.

1. Introduction

The angular spacecraft position determination technique of Delta Differential One Way Range (ΔDOR) has been in use over two decades [1]. The position of the spacecraft is measured relative to the predetermined reference frame of quasars by measuring the group delays using two intercontinental Deep Space Network (DSN) baselines. For the quasar, the group delay is obtained from the wide-band noise-signal. For the spacecraft, a pair of tones with about 100 MHz separation can be turned on, and these are used to determine the group delay to the spacecraft. The ΔDOR technique was successfully used for MER tracking, obtaining an accuracy of 2.0 nanoradian (nrad).

The accurate differential angular positions between quasars and a spacecraft can also be obtained using the technique of VLBI phase referencing [2], and recent VLBA results show that relative positions with accuracy < 0.25 nrad are possible. Hence, NASA initiated an investigation of the feasibility of this technique, which will be designated a VLBApr for VLBA phase referencing. Besides the possible increase in positional accuracy, the ten-element VLBA are invaseive since only the normal spacecraft tracking signals are needed, an accurate position could be determined with < 60 minutes of observation time, and the DSN telescopes were not tied up with this measurement.

The frequency used for the spacecraft tracking signals is 8 GHz (X-band); however the DSN is in the process of deploying K_a-band (32 GHz) tracking for the future. The 2005 Mars probe will be equipped with K_a-band and X-band transponders, and most future space probes will have only K_a-band. This higher tracking frequency will provide increased spectrum allocation and greatly reduced ionospheric effects. Improvement of tropospheric calibration using Water Vapor Radiometer (WVR) observations is also likely. These improvements will aid in both the ΔDOR and VLBApr techniques. If the VLBA is used for future space probe navigation, it must be upgraded to 32 GHz, and the results from critical sessions must be made available within 24 hours.

The absolute positional accuracy of most quasars is about 1 nrad (0.2 mas), and is one of the limitations in obtaining the absolute position of space probes. Hence, the VLBI groups at JPL, USNO, GSFC, NRAO and Bordeaux have initiated an international collaboration using the VLBA at 23 GHz and 43 GHz in order to determine a grid of quasars at 32 GHz with higher absolute accuracy than now available from the 8 GHz ICRF.

The final MER trajectory is one of the best determined deep space probe trajectories, and was chosen for evaluating the potential of the VLBApr technique. We report on observations on January 19, 21 and 23, 2004 which also included DSN ΔDOR observations for comparison. In §II we summarize the NRAO effort in order to obtain the spacecraft images and delays. In §III, the JPL effort used to incorporate the VLBA-measured delays into the Orbit Determination Program (ODP) is outlined. The comparison of the VLBApr and DSN ΔDOR astrometric results in given in §IV. A summary is given in §V and recommendations for future observations are suggested, and results from seven other spacecraft VLBApr observations are also mentioned.

2. VLBA Effort

The VLBApr theory and reduction is described in detail by Memo 1. Each scan was 1-min in length for the three quasars and MER-B. The approximate observing frequency was 8.3 GHz. The critical inputs for the spacecraft observations are: the frequency range of the telemetry signal, its polarization, and the spacecraft orbit. The communication line between JPL and NRAO was considerably enhanced over the last six months to facilitate these needed inputs for the observation and correlation of the VLBA data.

Both the quasar and spacecraft were observed with 2-bit sampling over a 16 MHz bandwidth, separated into 256 channels with 64 kHz width. The signal to noise for the quasar over 16 MHz bandwidth, and for the spacecraft over 64 kHz bandwidth was $50:1$ over a 1-min scan, producing errors already smaller than those associated with the variable troposphere refraction over each antenna.

The reduction and calibration of the data were similar to most phase-referencing VLBA experiments, and the theory and reduction steps are given in Memo 1. MER-B was used as the reference source and its interpolated phases were applied to the calibrators. The position of the calibrators was obtained by Fourier imaging of the calibration data, with subsequent CLEAN deconvolution, and the locations of the peak intensity on the image for the three sessions are shown in Fig. 1. The relative position of J0121+1149 (the ICRF quasar) with respect to the spacecraft agree within the ICRF position accuracy on Jan 19 (D). There appears to be a drift southward of the spacecraft by about 0.2 mas per day. The other calibrators have somewhat larger positional errors, and clearly have a relative displacement with respect to the ICRF source, but within the estimate errors.

This form of the VLBApr results is simple to obtain; however the measured position offset of the spacecraft can not yet be easily introduced into the navigation analysis package (ODP). The position offset is also tied to the correlator model.

The VLBApr results can be put into a form which is independent of the correlator model. As described in Memo 1, the total delay can be obtained for the spacecraft and the quasars, The major component is in the correlator model delay which includes the geometric delay, the atmospheric delay and the clock delay. During the reductions, the ionospheric delay and the position offset delay (derived from the image) are determined, and then any residual phase for the spacecraft and calibrators is converted to delay. The sum is then the total delay, and the difference between the total delays among the sources. A demonstration that the total delays are independent of the correlator model is demonstrated in Fig. 2. This shows the total delay differences obtained from the Jan 23, 2004 data set after two passes through the correlator when the spacecraft orbit had changed by about 30 mas, equivalent to 1000 psec at the longest baselines.

The quasar and spacecraft delays, with other information about the apriori calibrations, were written in an ascii format for delivery for the subsequent JPL analysis. An example of this output is given in the Appendix in Memo 1.

3. The JPL Analysis of the VLBA Total Delays

The VLBA-generated spacecraft and quasar total delays are based on the UTC time tag when the wavefront passed through the earth center. These were converted into differential range delays which are based on the time tags when the wavefront impinges at each telescope: This is the delay coordinate frame that is used in the ODP analysis package [1]. In the first stage of JPL analysis, the the necessary interfaces and procedures were developed to handle a complete experiment, analyze performance issues and the quality of the data [2]. The semi-automated procedures then converted the VLBA delay data into a form which is similar as the DSN ΔDOR observations and ready for use by the navigation team.

The navigation team then analyzed the VLBA delays as part of their complete data base which included the DSN ΔDOR observations of the same quasar (J0121+1149) and the spacecraft, as well

[1]J. S. Border, 'A Model for VLBA Spacecraft Delay Observables.' JPL Interoffice Memorandum 335-04-01-D, March 11, 2004.

[2]G. Lanyi, 'Initial assessment of the VLBA S/C-quasar differential angular measurement,' JPL Engineering Memorandum 335-04-03-D, June 4, 2004.

as ODP Doppler data. This quasar is within 0.3 mas of the ICRF grid which is used by the ODP models to derive the spacecraft location. The VLBA models for the atmosphere, ionosphere and clock were used, but JPL used its internal earth-orientation and ITRF frame definitions and its own realization of the MER-B orbit parameters [3]. This analysis of the VLBA delays were thus placed within the same system as the Doppler and ΔDOR observations and gives the spacecraft total delay with respect to the ICRF calibrator J0121+1149.

The differential residual spacecraft delay (DRSD) between the VLBA observations and the ODP spacecraft delay has three main contributions: The offset position of the spacecraft from that assumed by the ODP models, d_p, which includes an possible offset of the ICRF frame used by the VLBA and that used in the ODP of < 0.3 mas, the delay offset associated with atmospheric delay differences between the quasar and the spacecraft, d_r and other small errors associated with the antenna position errors and earth-orientation parameter errors, d_b. These terms are described in Memo 1, Eq. 8.

4. Comparison of VLBApr DSN ΔDOR with the Navigation Results

The DRSD is a time varying function for each baseline. In Fig 1a we show the average absolute values of the DRSD for the VLBA observations for each baseline as a function of baseline length, for all three days, each of duration 4 hours. These points show a rough linear slope with baseline length which is indicative of a position error, d_p. The histogram of these delay residuals, converted from baseline length into an angular performance ($\sim 1/5$ fringe size) is shown in Fig 1b. The mean value is 1.9 nrad.

Some component of the DRSD may be caused by an offset from the assumed ODP position. For example, an offset of 0.2 mas (well within the ODP uncertainty) would produce a delay residual at 10000 km up to 20 psec. In Fig 2a we show the average absolute values of the DRSD for the VLBA observations as a function of baseline length, *after fitting for a constant spacecraft orbit offset* over the observation period. The remaining delay residuals are probably dominated by atmospheric refraction differences between the spacecraft and quasar. Fig 2b shows the histogram of residuals as a function of angular performance. The mean value is 1.4 nrad. If the four largest outliers are removed, the mean value is 1.0 nrad.

The conclusions from Figure 2a suggest that for the VLBAph residual delays have a floor rms of 6 psec and a linear term which is 17 psec at 10000 km. A similar analysis of the DSN ΔDOR post-fit residual scatter after comparison with the ODP-derived orbit, and removal of a possible position shift shows a residual scatter, is approximately 40 psec for a baseline of 10000 km. This is about twice as large as the residual delay scatter from the VLBA observations.

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[3] T. J. Martin-Muir, 'Navigation Analysis of the MER-B VLBA Data', A JPL Presentation, September 24, 2004

Fig 3 shows the 3-σ error ellipses for the VLBAph and DSN ΔDOR positions when placed on the B-plane which is most convenient from the ODP analysis, and can be converted into an approximate angular scale in the sky. For the DSN alone and for the VLBA+DSN (dominated by the VLBA), the 3$\times$ rms error is 0.24 x 0.48 km or 1.2 x 2.4 nrad in position angle - 20°. The agreement in the spacecraft position among all of the techniques are in good agreement, less than 1-σ of the combined errors. The orientation of the error ellipse scales approximately with the resolution of the VLBA and DSN observations; hence north/south accuracy will always be a factor of two worse than that for the east/west direction. These observations were made over several days under different observing conditions, so that the behavior on different days are not yet available.

5. Summary and Recommendations

The VLBApr technique performed well on the MER-B trajectory and provided angular spacecraft coordinates within the statistical uncertainty of the predetermined trajectory. The formal error in right ascension is 1.2 nrad for the VLBA is smaller than the corresponding DSN error of 2.4 nrad; this factor of two agrees with the relative values of the delay residuals for the two techniques, described above. However, both techniques are already more limited by the uncertainty of apriori quasar position than in their experimental errors. Hence, the improvement of the ICRF catalog, especially at 32 GHz should have high priority. It is also important to observe a quasar that is within 3° of the spacecraft with an accurate position. This may be require a quasar search and position determination at least one month in advance of the intended tracking period.

Based on the analysis of this and other VLBApr spacecraft observations which are described in Memo 3, the following comments may be useful:

1. The measured total delays are insensitive to the accuracy of the input orbit, and offsets as large at 100 mas are routinely handled.

2. With the recent improvements in the VLBA correlator model, we believe that the spacecraft offsets measured from an image are accurate to < 0.3 mas, and can be used instead of the total delay for updating the spacecraft position.

3. The spacecraft signal is strong, often having more SNR than the quasars. Any signal that is used for spacecraft telemetry will clearly be sufficiently strong for VLBA interferometry. The data is atmospheric-limited after only a few minutes of integration.

4. Observations south of $-10°$ will have larger errors, especially in the north-south direction, as shown by a Stardust spacecraft observation which is available. Observations of MGO or Odysses near Mars in early 2005 will provide data with Mars at Declination

5. The quality of the results depend on the proximity of the quasar to the spacecraft. However, even near the galactic plane, it is rare not to have a quasar within 5° of the target. As described

above, VLA/VLBA search observations can be made at least one month before the spacecraft observations to find additional quasars, or to determine a quasar position within 0.5 mas of the ICRF frame. With the MARK-5 system we expect to have significant increased sensitivity so that quasars can be found sufficiently close to a target to reduce this possibility. Since the VLBA observations are non-invasive to the spacecraft operation, session times can be chosen when the spacecraft is passing near a suitable quasar.

6. The Mer-B VLBA experiments were four hours in length. We expect that 30-min observations, especially at the highest spacecraft elevations available, will provide more than sufficient accuracy, and these tests are continuing.

7. At the new DSN tracking frequency of 32 GHz, the phase errors will be a factor of four larger than those at 8 GHz. This will make phase referencing somewhat more difficult since phase ambiguities will be more likely. See Memo 4 for details in the suggested VLBA 32 GHz observations.

Finally, the VLBA with 10 telescopes and 45 baselines has built-in redundancy for the reliability of results. The large number of baselines is important for determining unambiguous offset spacecraft positions, even in the presence of large phase residuals, that are needed to obtain unambiguous total delays. At the higher frequency, even the use of the five or six antennas in the SW USA will be sufficient to obtain 1.0 nrad accurate positions.

References

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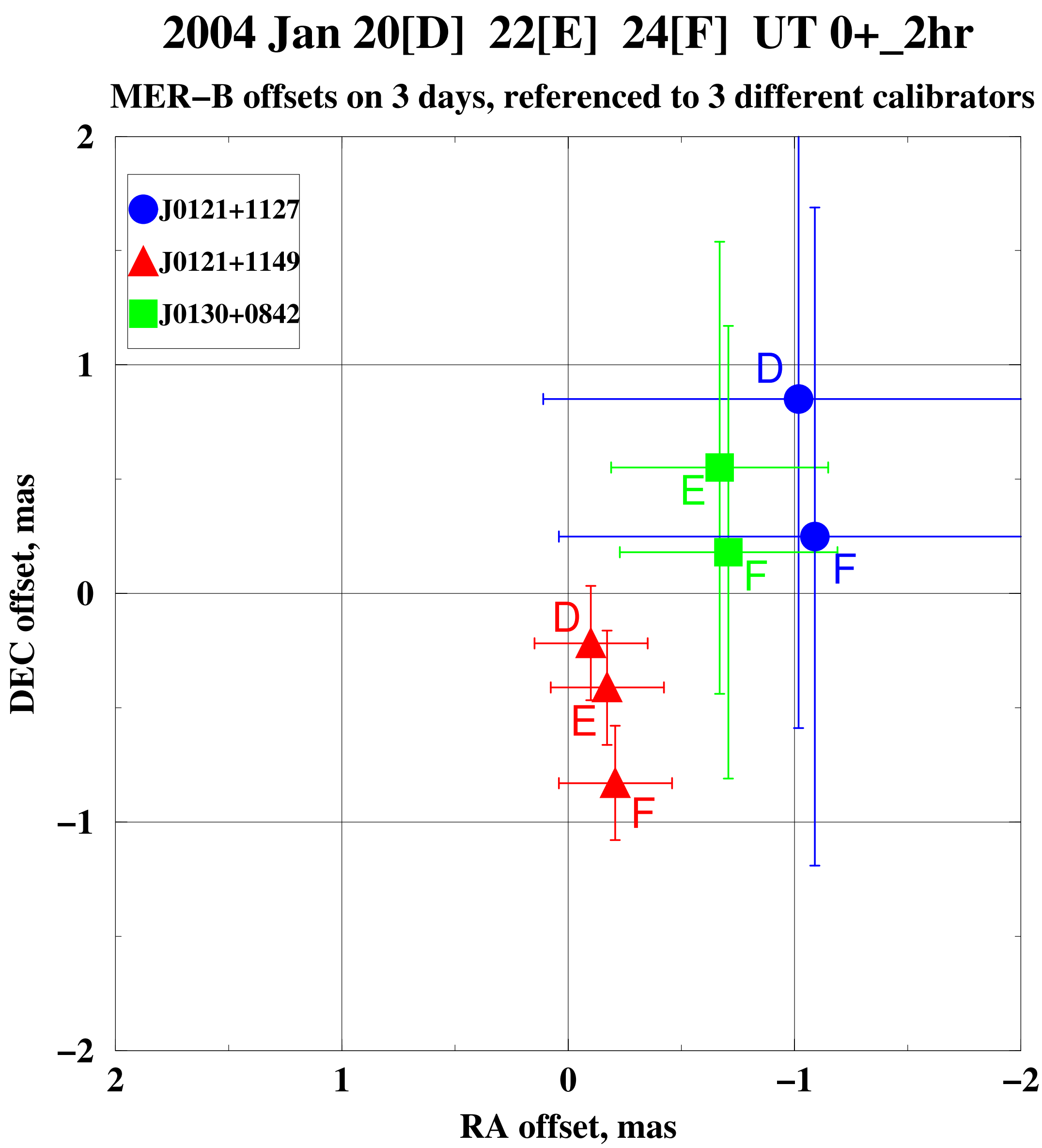

Fig. 1.— **The relative position of the three quasars using the spacecraft as the reference source**. Each quasar is shown by the indicated color, and the letter code gives the observing session: D=Jan 19, E=Jan 21, F=Jan 23. The estimated position errors of the three quasars are shown by the error bars. Hence the quasar offsets from the phase center are consistent (especially for J0121+1149) with their estimate errors. Ignoring the quasar offsets, the internal consistency of the relative positions for each quasar among the three days suggests that the VLBA measured spacecraft position, with respect to the assumed orbit position, moved south by 0.8 mas over the four day period. Since the three quasars surround the spacecraft in the sky, large atmospheric induced position offsets should have produced more scatter in each quasar drift.

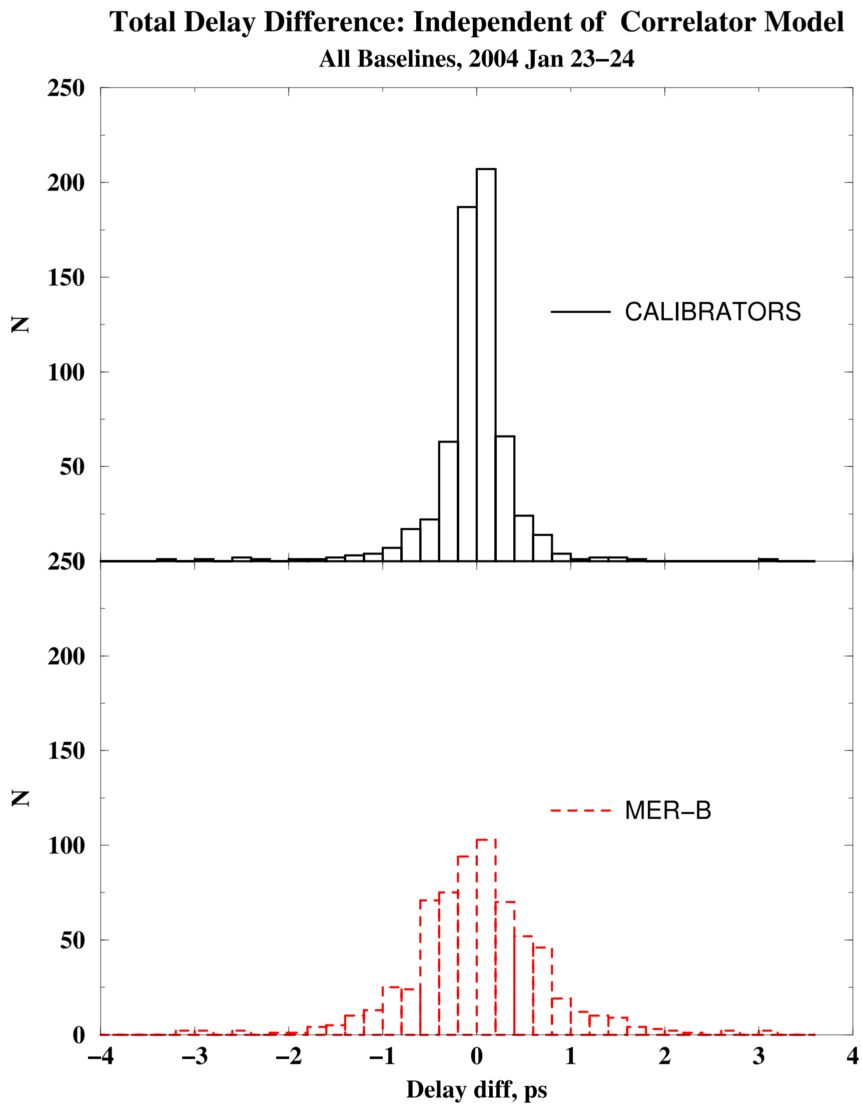

Fig. 2.— **The total delay difference from two correlation passes of the Jan 23, 2004 experiment**. The spacecraft orbit differed by about 30 mas in the two passes. (top). The histogram of the delay difference for all baselines for the three quasars. The rms scatter of 0.3 psec is typical for two correlation passes with no changes in the correlation model that would affect the quasars. (bottom) The histogram of the delay differences from all baselines for Mer-B. The rms scatter is 0.8 psec, somewhat larger than for the quasars, but at a level of 0.01 nrad (0.005 mas) in effective position error. The spacecraft position difference was 30 mas for the two correlators, equivalent to about 1000 psec at the longer baselines.

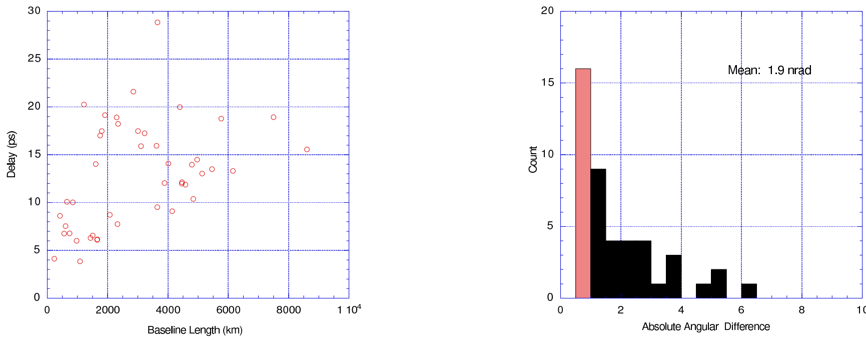

Figure 1. a) Prefit absolute differential residual delays as the function of the baseline length; b) Distribution of prefit absolute angular difference.

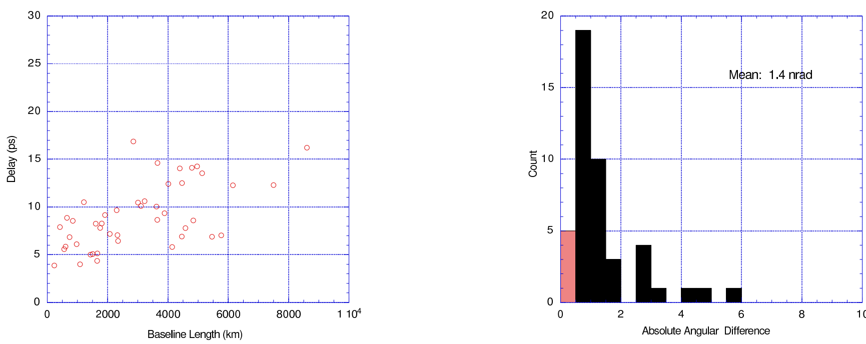

Figure 2. a) Postfit absolute differential residual delays as the function of the baseline length; b) Distribution of postfit absolute angular difference.

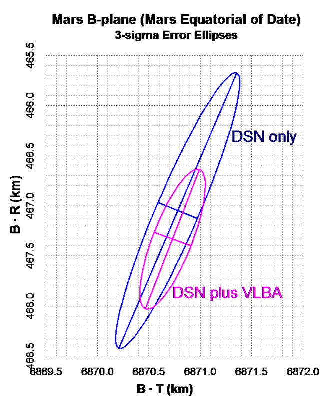

Figure 3. B-plane spacecraft position with 3-σ error ellipses. The grid spacing is 0.1 km (0.5 nrad). The outer ellipse represents the DSN standard solution. The VLBA data is included in the inner ellipse solution.