

# ASTRA

## interdisciplinary study on enhancement of end-to-end Accuracy for Spacecraft TRACKing techniques



### Executive Summary

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## 1. CONTEXT

Knowing where a spacecraft is, and where it will be at a future epoch is vital to successful operations of space missions. Arriving on time at the right place and with the desired velocity is the essence of space navigation, but reaching the exquisite precisions required by current and future missions is never a routine matter. Any space navigation system rests on two pillars: an accurate model of the spacecraft dynamics and a set of high precision observable quantities providing indirect information on the spacecraft state. Both these aspects have been examined in this study, with the goal of improving the orbit determination of ESA's probes in view of future, more demanding needs from mission control and scientific investigations.

The orbit determination of a probe in deep space relies almost entirely on radio measurements enabled by a complex tracking system involving one or more ground stations and the onboard transponder. Three are the tracking techniques currently being used for the determination of the spacecraft state vector, namely integrated Doppler, ranging and  $\Delta$ DOR. Current ESA on-board and ground systems provide the radial component of the spacecraft velocity with respect to the ground antenna with accuracies in the order of 0.1 mm/sec, while the range from the antenna to the satellite is known with an accuracy of a few meters. Interferometric techniques ( $\Delta$ DOR) involving two widely separated ground antennas are used especially in the cruise phase to determine the angular position of the satellite in the plane of sky, with accuracies of about 15 nanoradians (or 2.3 km at a distance of one astronomical unit).

The navigation accuracy ultimately depends on the quality of the observable quantities and on the adequacy of the dynamical model to match the quality of those observables. In this study we have identified methods and systems capable of improving the accuracies of the three radiometric tracking techniques by one order of magnitude. We have also indicated the modifications needed on current orbit determination codes, so that the increased observational accuracies can reverberate into improved spacecraft navigation, to the benefit of future, demanding scientific missions of the Agency.

## 2. GOALS AND APPROACH

The study addressed interdisciplinary aspects of spacecraft tracking involving four key areas: ground station, on-board TT&C systems, media calibration and modelling of the observables in the orbit determination process. The work was structured in three main steps:

1. Consolidation of the error budget for each considered tracking techniques;
2. Identification of the major error contributions;
3. Identification of systems and methods for the cancellation or reduction of the major error sources.

The consolidation of the error budget for each considered tracking technique was carried out

using data available from ESA's deep space mission Rosetta. The analysis allowed the characterisation of the performances of current tracking techniques at X-band frequencies (8.4 GHz) in the ESA system. Ka-band data at 32-34 GHz, available from the Cassini-Huygens mission (NASA/ESA/ASI), were used to better isolate some of the most relevant noise contributions (interplanetary plasma and troposphere) in the currently employed radiometric techniques.

The first part of the study provided a consolidated evidence for the dominant noise or systematic contributions affecting current ESA tracking systems:

- Interplanetary and ionospheric plasma noise (affecting range, range rate and  $\Delta$ DOR);
- Tropospheric noise due to water vapour (affecting mostly range rate and  $\Delta$ DOR, and marginally also range);
- Numerical noise due to finite arithmetic in orbit determination codes (affecting only range rate);
- Multipath effects and time variable group delays in the ground and onboard antenna systems (affecting range);
- Phase ripples across the measurement bandwidth (affecting  $\Delta$ DOR).

At the current level of accuracies, noise due to the ground and spacecraft electronics is well below the current and future accuracies of Doppler systems. No difference was apparent between data collected at the ESTRACK and DSN antennas. Thanks to the multifrequency radio system of the spacecraft Cassini, supported by ground calibrations of the wet troposphere, the Doppler error budget was broken down to its main components in a precise quantitative assessment. The results have been applied to the Doppler residuals of the spacecraft Rosetta, with very good overall agreement (see Figure 2-1). Ground and spacecraft systems is an important factor in range and  $\Delta$ DOR error budget, causing jitter, biases and phase ripples. The range jitter in Rosetta data is plotted in Figure 2-2 together with the theoretical curve.

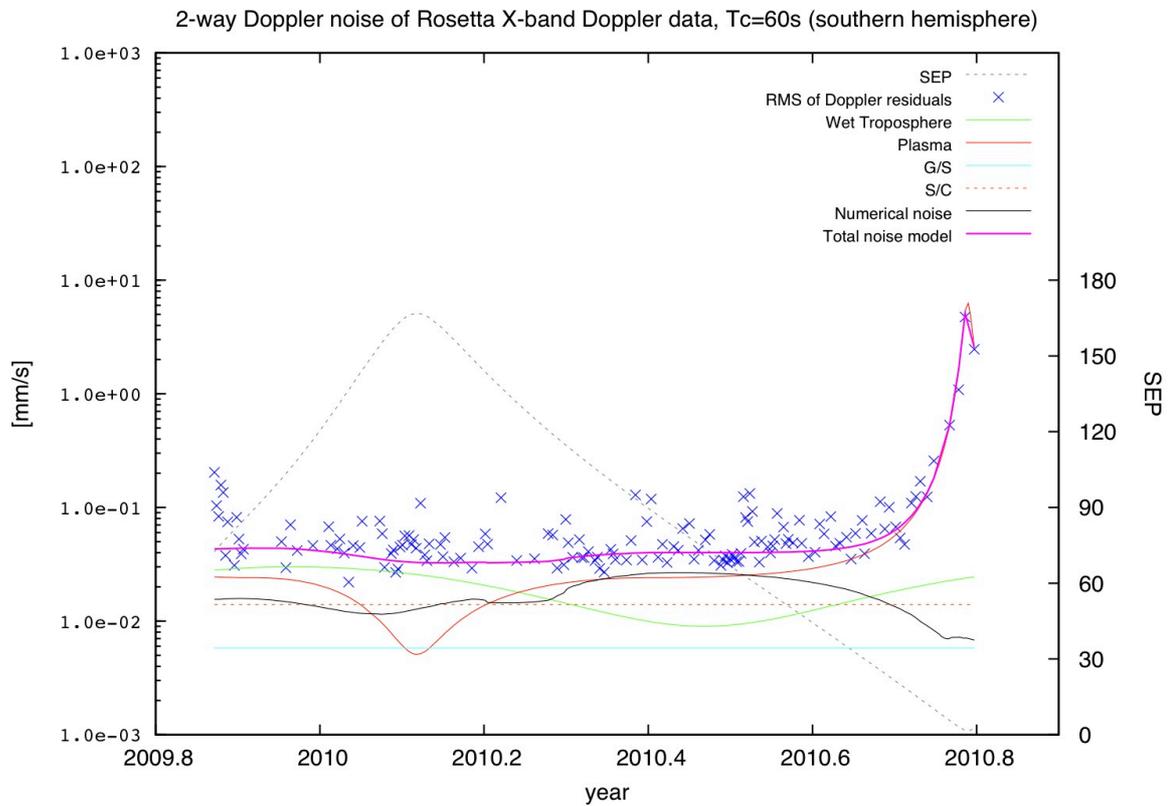
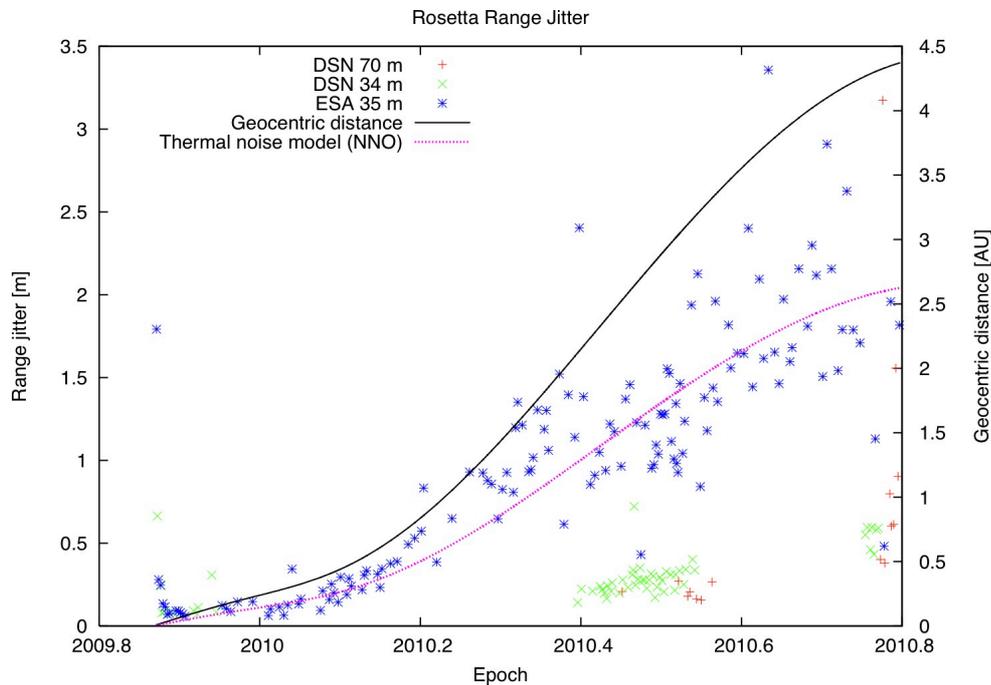


Figure 2-1 Root mean square value of Rosetta Doppler range rate residuals at 60 s integration time and main error sources (New Norcia). Each point in the plot refers to a single tracking pass.



**Figure 2-2 Rosetta range jitter (data points), shown together with the geocentric distance (black) and theoretical jitter (magenta) for New Norcia ground station, which has a loop bandwidth of 0.126 Hz. The green and red points refer to DSN antennas, where a smaller bandwidth is used.**

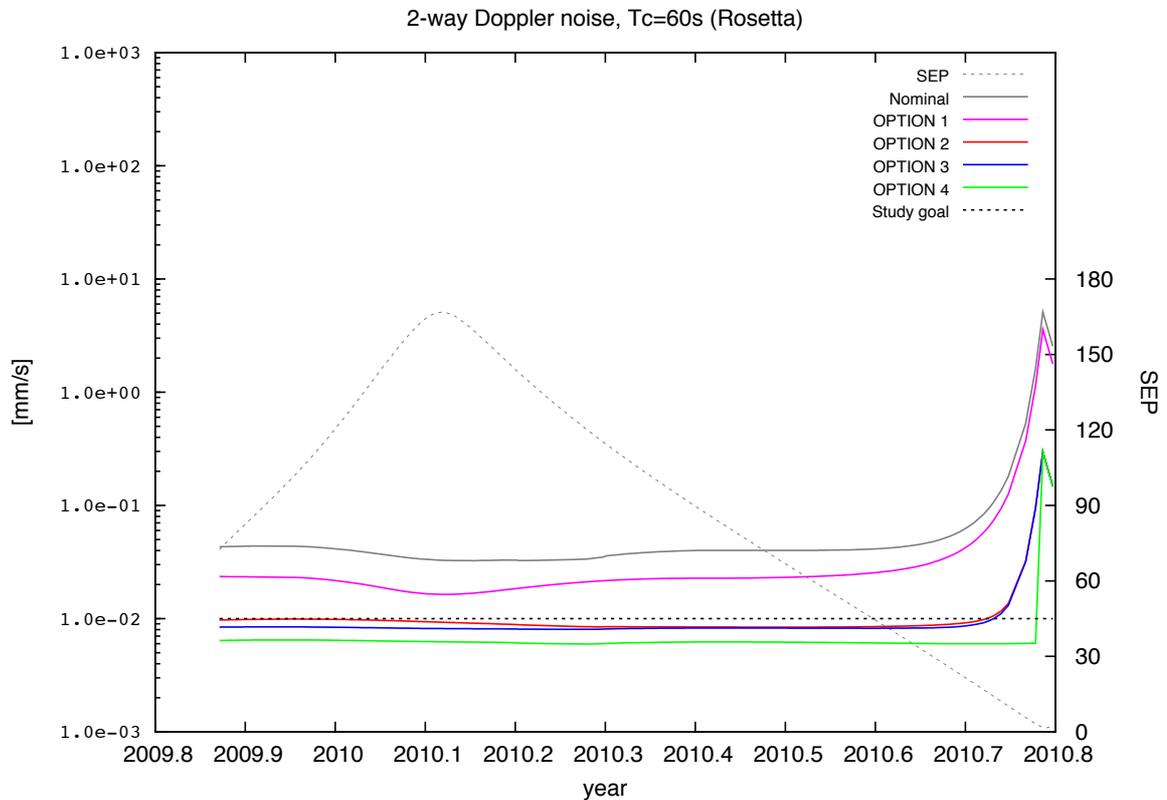
In the second phase of the study, the dominant error sources were analysed with the goal of building guidelines and strategies suitable to the mitigation of their effects. We have analysed four operational scenarios applicable to current and future missions of the Agency. Each scenario entails improvements in each of the key areas (ground station, on-board TT&C systems, media calibration and orbit determination codes), with increasing performance from case 1 to 4. Two of the proposed systems provide the desired improvement by a factor of 5 or 10 for each of the three tracking techniques under most or all operational scenarios. In order to offer a broader set of options, we have outlined also architectures that, although do not fully meet the targets of the study, still represent a significant improvement of current tracking systems. The requested accuracy for each option implies modifications, quite substantial in some cases, to the existing space and ground equipment. All these modifications have been analysed in terms of complexity and development time and therefore categorised into four levels, depending on the overall impact. The selected options are:

- **OPTION 1** provides some improvement over the accuracies attainable with the current systems, but without meeting the study goals. It may be referred to as a “BepiColombo with enhanced ground system”, as it does not entail changes in the TT&C flight hardware of the BepiColombo mission (no Ka-band uplink). Tropospheric calibrations (now based on

seasonal models) are accomplished by means of commercial microwave radiometers, while numerical noise is reduced by recompiling existing codes in quadrupole precision. The variability in the station group delay is reduced by changing from a long to medium loop calibration. Internal calibrations based on BWG geometry and a priori tables provide an abatement of phase ripple by a factor of 5 in  $\Delta$ DOR measurements.

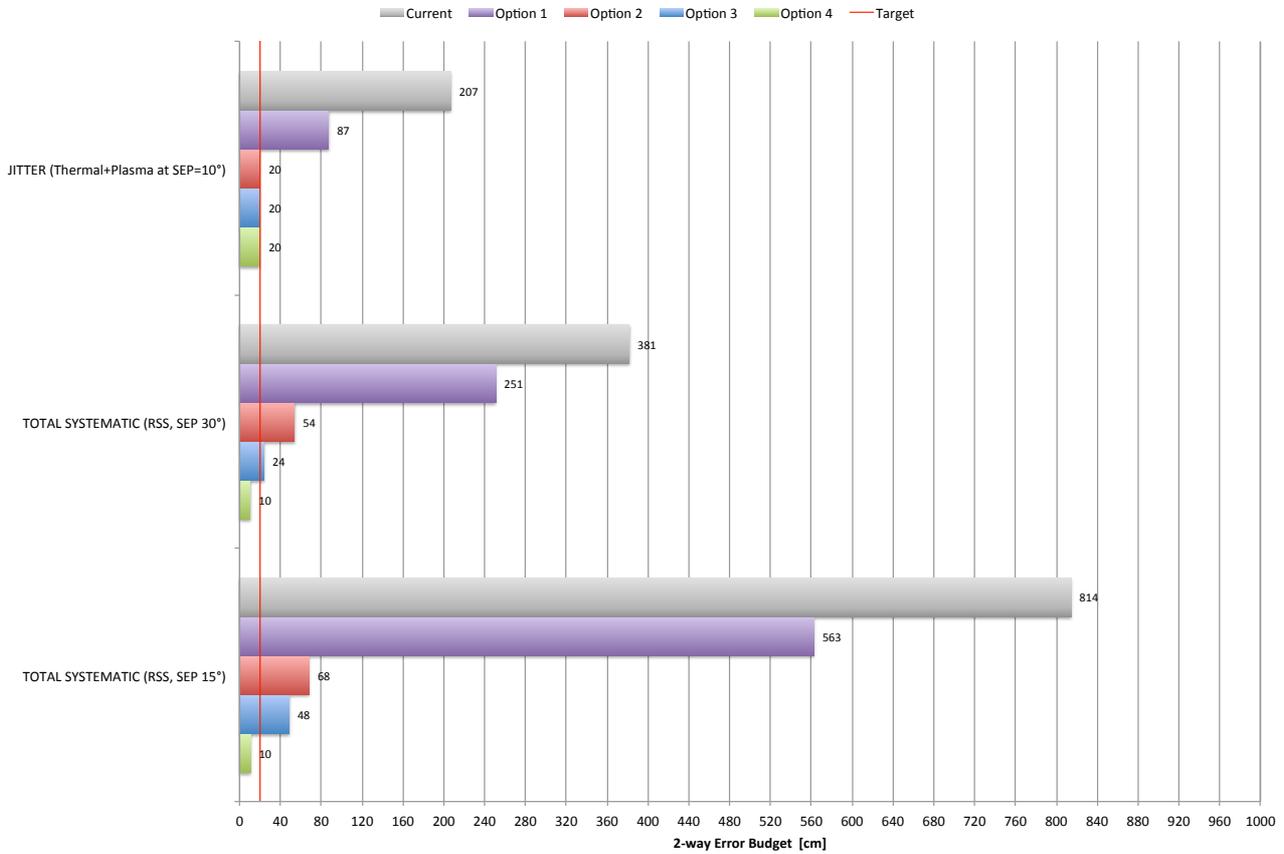
- OPTION 2 is an intermediate configuration that entails modification also to the flight hardware. The resulting radiometric link is capable of meeting most, but not all requirements of the study, with limited impact on the current tracking network. It is a medium performance system, with possible applications to future ESA's deep space missions such as JUICE/Laplace. Ka-band uplink is required (although not in the multifrequency configuration). Numerical noise is now reduced thanks to an improved time representation in OD codes. The ground station bias is calibrated by means of an automated mapping of loop group delay (based on wideband PN ranging), while the bandwidth for  $\Delta$ DOR open loop recording increases to 152 MHz bandwidth for better quasat SNR at X and especially Ka band.
- OPTION 3 represents the proposed future state of the art in terms of both precise spacecraft navigation and scientific applications: this high-performance radiometric link is capable of meeting the requirements of the study under most, but not all, operational conditions. In addition to the configuration of Option 2, advanced microwave radiometers are now employed for tropospheric calibration. Calibration of ground station bias is made with real-time monitoring and spread spectrum ranging. In this option the flight hardware must supply a 152 MHz bandwidth and phase ripple is strongly reduced thanks to spread spectrum spacecraft DOR signal.
- OPTION 4 provides the ultimate accuracy in terms of both precise spacecraft navigation and scientific applications. It is based on the experimental capabilities of the mission BepiColombo, entailing a multifrequency link system at X and Ka band, augmented for spread spectrum ranging and  $\Delta$ DOR.

The improvements provided by each option for the Doppler observables are summarized in Figure 2-3, which shows what the Rosetta Doppler noise would be against the study goal (20 cm two-way), should the proposed systems be in place.



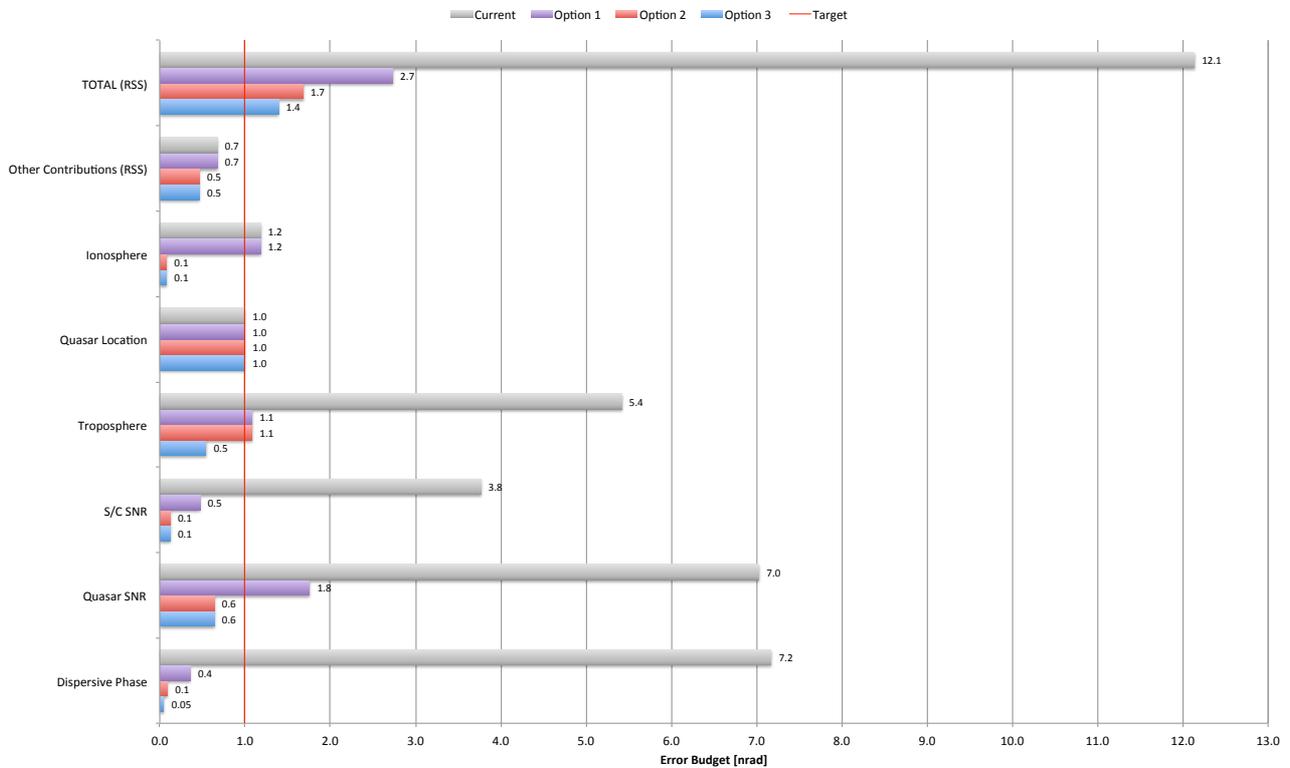
**Figure 2-3 Expected end-to-end Doppler noise for current Rosetta tracking system (grey) and proposed options 1-4. The curves show the noise that would have been experienced if the proposed systems would be in place. Media noise contributions refer to a worst-case configuration (summer day-time conditions for troposphere and 15° SEP for plasma noise). Plasma noise is strongly reduced when using Ka-band (option 2 and 3) but it still a limiting factor for small SEP angles (e.g. below 10°). It can be almost completely canceled out up to about 3° of SEP only with a multifrequency link configuration (option 4).**

Similarly, Figure 2-4 shows the attainable accuracies in ranging measurements both in terms of jitter and systematic contribution. Since the latter is strongly influenced by plasma, we have considered both a rather unfavorable condition (SEP=15°) and a more benign one (SEP=30°). Interplanetary plasma turns out to be a limiting factor for range measurements even for Ka-band systems for SEP less than 30°. If the study goal (20 cm two-way) needs to be met under almost all operational conditions, a multifrequency links configuration (Option 4) is the only available choice.



**Figure 2-4 Bar chart for range noise contributions, for current system (grey) and proposed options 1-4. The noise has two components (random one and systematic). The study goal can be reached for SEP less than 30° only if a multifrequency X/Ka-band ranging is used (Option 4). The larger error in Option 2 is due to G/S biases. Using wideband ranging widely reduces thermal noise in option 2, 3 and 4.**

For ΔDOR systems there are some intrinsic limitations related to differential tropospheric noise and uncertainties on the quasar location. A lower bound to the attainable accuracy is found at about 1.4 nanoradians (just above the study goal of 1 nanoradian), even in the more advanced configuration. However the achievable performances still represent an improvement by roughly a factor of 10 with respect to the accuracy of current ΔDOR system of the Agency (see Figure 2-5).



**Figure 2-5 Bar chart for  $\Delta$ DOR noise contributions, for current system (grey) and proposed options 1-3 (for  $\Delta$ DOR Option 4 coincides with Option 3).**

### 3. MAIN RESULTS

The study has identified five main sources of errors limiting the accuracies of current ESA tracking and orbit determination systems: interplanetary plasma, tropospheric water vapour, numerical noise, variable group delays in the ground and onboard RF systems, and phase ripples across the measurement bandwidth. Propagation noises can be effectively reduced by a factor of 10 by using Ka-band radio links to the spacecraft and microwave radiometers at the ground antenna. Guidelines for the reduction of numerical noise in orbit determination codes entail either the use of extended (quadruple) precision or an improved representation of time. Variable group delays in RF systems can be successfully tackled by adopting spread spectrum ranging schemes with increased chip rate. Accurate calibrations of the phase delays across the measurement bandwidth or the generation of spread spectrum DOR signals by the onboard transponder would significantly reduce the effect of phase ripples in  $\Delta$ DOR measurements.