IMPROVED DOPPLER TRACKING SYSTEMS FOR DEEP SPACE NAVIGATION

Luciano Iess[(1)], Mauro Di Benedetto[(1)], Manuela Marabucci[(1)], Paolo Racioppa[(1)]

luciano.iess@uniroma1.it
mauro.dibenedetto@uniroma1.it
manuela.marabucci@uniroma1.it
paolo.racioppa@uniroma1.it

[(1)]Dipartimento di Ingegneria Meccanica e Aerospaziale, Sapienza, Università di Roma,
Via Eudossiana 18, Rome, 00184 Italy

ABSTRACT

Range rate is the most commonly used tracking observable for navigation of deep space probes. Measurements of the Doppler shift of a microwave carrier provide information about the spacecraft-Earth relative velocity along the line of sight. Currently ESA and NASA Doppler tracking systems rely on two-way coherent radio links at X-band (7.2-8.4 GHz). The average measurement accuracy ranges from 0.1 to 0.02 mm/s at 60 s integration time, but it dramatically degrades approaching superior solar conjunctions due to the high sensitivity to plasma noise. Tracking data from the Cassini and Rosetta missions provided a large data set for an extensive analysis of the main error sources affecting Doppler observables. We identified the three main contributions in the plasma (interplanetary and Earth ionosphere), tropospheric and numerical noise. The separation between dispersive errors and all other contributions has been possible thanks to multi frequency observations at X- and Ka-band available from the Cassini radio science experiments. Characterization of the tropospheric noise is based on measurements from the Advanced Media Calibration system developed at JPL. On the basis of the consolidated error budget, we defined the architectural guidelines for an improved Doppler tracking system. The proposed solutions allow measurements of the spacecraft range rate with accuracy of 0.01 mm/s at 60 s integration time, or better, in almost all operational conditions.

Keywords: Doppler, range rate, noise, error budget, tracking

INTRODUCTION

Knowing where the spacecraft is and where it will be at a future time is the ultimate goal of space navigation. So far, the orbit of deep space probes has largely relied on range rate measurements, a reliable and relatively simple tracking technique. The range rate is generally obtained by measuring the frequency shift of a microwave carrier sent to the spacecraft from a ground antenna and coherently retransmitted back by the spacecraft. The current ESA and NASA tracking systems rely on coherent, two-way radio links at X-band (7.2-8.4 GHz), which however are quite sensitive to plasma noise and therefore exhibit a strong dependence on the solar elongation angle (also called Sun-Earth-probe, or SEP angle). A detailed analysis of Doppler system performances showed that at X-band the one-way Allan deviation is lower than $\sim 10^{-13}$ at 1000 s integration time when SEP > 30° [1]. This corresponds to 3×10^{-2} mm/s range rate accuracy (one-way) but degrades dramatically when the ray path goes deeper in the solar corona. On the opposite, when approaching solar oppositions plasma noise decreases significantly and other noise sources become relevant.

Recently ESA's General Studies Programme (GSP) funded a study ("*Interdisciplinary Study for Enhancement of the End-To-End Accuracy for Spacecraft Tracking Techniques*"), requiring a systematic assessment of ESA's tracking system accuracies (range, range rate and Delta-DOR). The study goal was to build guidelines for future improvements of the Agency's tracking systems, setting the target accuracies to 0.01 mm/s at 60 s integration time for Doppler (two-way), 20 cm for range and 1 nrad for Delta-DOR. The study was a collaborative effort of Sapienza University of Rome (prime contractor), ALMASpace, BAE Systems and Thales Alenia Space Italy.

The work presented here focuses only on the Doppler technique. In the first part of the study we consolidated the Doppler error budget identifying all noise sources entering range rate observables. This task has been accomplished primarily through a statistical analysis of a large data set available from the Rosetta (ESA) and Cassini (NASA/ESA/ASI) missions. This analysis provided an accurate and robust breakdown of the main error contributions, which were compared against Cassini X-band data from the Saturn tour (spanning over six years) and Rosetta X-band data acquired during the interplanetary cruise (spanning one year). The excellent agreement between predicted and observed noise provided the required validation of the error models used to build guidelines and strategies for future upgrades of ESA's deep space tracking systems. We identified architectural solutions offering different levels of improvements, often capable to meet or exceed the study goals. Should the proposed solutions be implemented, the navigation accuracies of planetary missions could be significantly increased.

DATA SET

The breakdown of the range rate error budget is based on available radio-metric measurements from the Rosetta and Cassini missions. Rosetta is a cornerstone mission of ESA's long-term space science programme. The spacecraft was lunched on Mar. 2, 2004 and is set for a rendezvous with the Comet 67/P Churyumov-Gerasimenko in 2014 after a complex trajectory that includes four gravity assists. Rosetta Flight Dynamics (FD) team provided us both Doppler residuals and received sky frequencies spanning from Nov. 2009 to Oct. 2010, when the spacecraft was in the initial cruise phase (the data set begins just two days after the last Earth gravity assist, on Nov. 13, 2009). While Rosetta observations are only available at X-band, crucial information about plasma noise has been inferred from multi frequency measurements at X- and Ka-band during two Cassini radio science experiments carried out in the cruise phase between the orbits of Jupiter and Saturn. The two experiments were a Gravitational Wave Experiment (GWE1) from Nov. 26, 2001 to Jan. 4, 2002 and a Solar Conjunction Experiment (SCE1) from Jun. 6, 2002 to Jul. 5, 2002. Because of the dispersive characteristics of interplanetary plasma (inversely proportional to the square of the frequency), uplink and downlink plasma noise contribution can be separately evaluated from the three simultaneous X/X (7.2-8.4 GHz), X/Ka (7.2-32.5 GHz) and Ka/Ka (34-32.5 GHz) links [2]. This multi frequency system was planned to support other radio science and gravity experiments during all the Saturnian phase, covering all range of SEP angles. Unfortunately an unrecoverable malfunction on 2003 caused the definite loss of the Ka/Ka link; only data from the X/X and X/Ka links are therefore available after SCE1. They were mainly used to validate the error models over a large time basis.

The data set is complemented by readings of JPL's Advanced Media Calibration system (AMC) that provides accurate calibrations of dry and wet tropospheric path delay. Although the AMC system comprises a suite of meteorological instruments, its core is an ultra-stable microwave radiometer (MWR) for measurements of the sky brightness temperature. Such instrument was expressly developed at JPL in support of Cassini radio science experiments. The combined operation of a multi frequency link and AMC during SCE1 ended up in a ~9×10^{-3} mm/s range rate accuracy at 60 s of integration time (two-way, corresponding to Allan deviation of ~ 1.5×10^{-14} at 1000 s), a value otherwise achievable only near solar opposition [3].

NOISE ON DOPPLER MEASUREMENTS

In principle, range rate measurements are both affected by random and systematic errors. However analyses and the experience have shown that at timescales ~ 1-1000 s systematic contributions are always negligible. Exceptions may be found only in the very low-frequency bands (10^{-6} to 10^{-4} Hz), the timescales of interest of some radio science experiments [4]. In this work systematic contributions have not been addressed further.

The strongest effect for the stability of a link at X-band (λ ~ 3.5 cm) is due to fluctuations of the refractive index δn, caused by irregularities in the solar wind and to a less extent the ionospheric plasma. For a cold unmagnetized plasma $\delta n = -\lambda^2 r_e \delta n_e / 2\pi$ and the phase perturbation on the signal carrier is $\delta\phi = -\int \lambda r_e \delta n_e dz$, where λ is the wavelength, r_e is the classical electrical radius and δn_e is the electron density fluctuation along the line of sight z. Perturbations on the carrier phase mimic a time-varying distance changes and therefore affect range rate measurements:

$$\delta\dot{\rho} = \frac{\lambda}{2\pi}\delta\dot{\phi} = -\int \frac{\lambda^2}{2\pi} r_e \frac{\delta n_e}{\delta t} dz \qquad (1)$$

Equation 1 evidences the well known fact that the adoption of higher frequency radio links effectively reduces plasma noise. The Cassini mission has demonstrated also that a tracking system based on three simultaneous links, namely X-band up- and downlink (X/X), X-band uplink and Ka-band downlink (X/Ka), and Ka-band up- and downlink (Ka/Ka), provides a “plasma-free” (non-dispersive) time series of the fractional frequency shift $y_{nd}(t)$. The most significant results were obtained during Cassini SCE1, were the plasma noise was cancelled out up to 5-8 solar radii [2]. The loss of the Ka/Ka link in 2003 prevented a complete characterization of the plasma noise over the full range of SEP angles when the spacecraft started orbiting about Saturn (2004). During gravity science experiments, occurred at intermediate SEPs, only the X/X and X/Ka links were used and such incomplete scheme allows a precise calibration of plasma noise only in the downlink path. However if the correlations between the path delays in the uplink and downlink are neglected, one may scale the measured downlink contributions at X-band uplink (7.2 GHz) and still obtain a good approximation of the total plasma noise in a two-way link. Figure 1 and eq. 2 show the empiric model (expressed in Allan deviation at 60 s integration time) we derived for plasma noise at X-band by least square fitting SCE1, GWE1 and tour data of Cassini. Instead of the large drop expected when approaching solar opposition, we observed a noise plateau, having an Allan deviation of $\sigma_y = 1.27 \cdot 10^{-14}$ at 60 s integration time, corresponding to a range rate error of 3.8×10^{-3} mm/s. This could be due to the presence of unmodeled phenomena such as compressive magnetosonic waves that are not co-moving with the solar wind [5]. (This behaviour was not investigated further). A fit of the available data provided the following plasma noise model:

$$\begin{aligned}
&\sigma_y(60s) = 1.76\cdot10^{-14}\sin(SEP)^{-1.98} + 6.25\cdot10^{-14}\sin(SEP)^{0.06} && 0° \le SEP \le 90° \\
&\sigma_y(60s) = \left(1.76\cdot10^{-14} + 6.25\cdot10^{-14}\right)\sin(SEP)^{1.05} && 90° < SEP \le 170° \\
&\sigma_y(60s) = 1.27\cdot10^{-14} && 170° < SEP \le 180°
\end{aligned} \qquad (2)$$

This model provides the Allan deviation as a function of SEP angle and therefore is strictly valid only for missions in the outer solar system. In the inner solar system SEP should be replaced by

SPE and fitting coefficients should be increased up to a factor of the square of the reciprocal of the heliocentric distance.

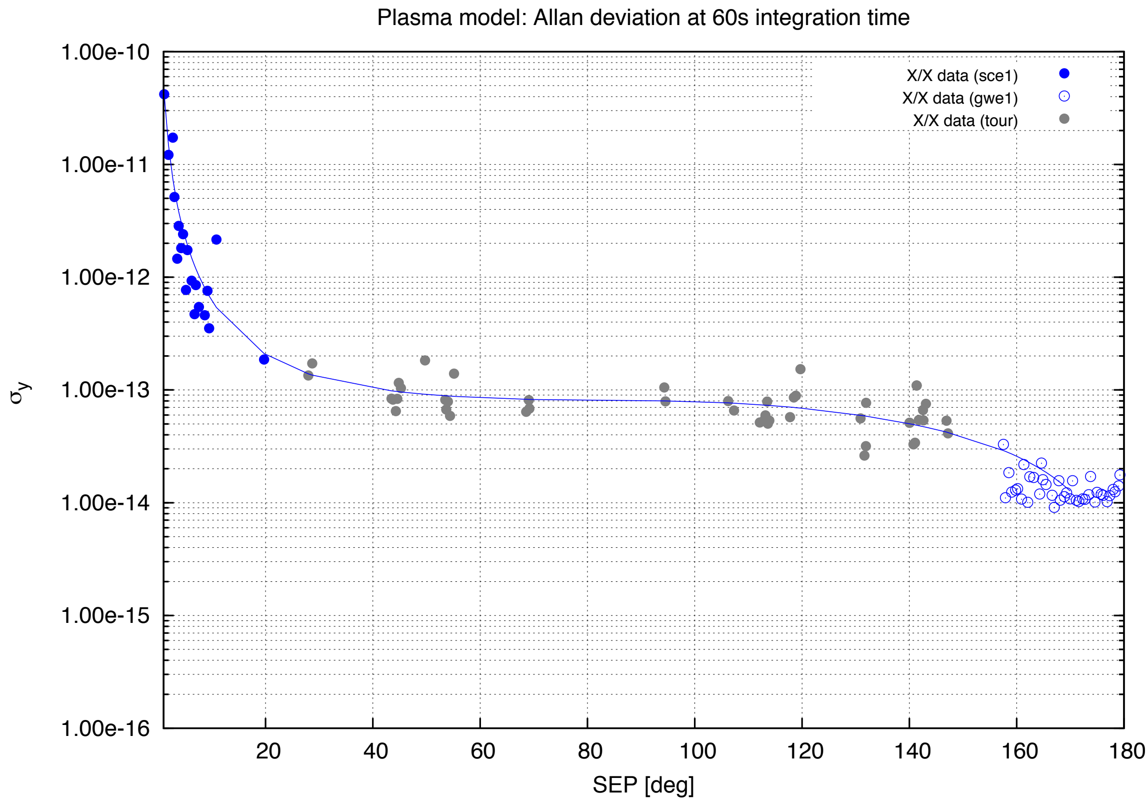

Figure 1: Plasma noise model at X-band. The curve is obtained by least square fitting plasma noise measured with Cassini multi frequency radio system. Blue dots refer to cruise radio science experiments when the three links (X/X, X/Ka and Ka/Ka) were all available. Grey dots come from the incomplete link at X/X and X/Ka bands during the Saturn phase.

Fluctuations of the tropospheric refractive index are another severe limiting noise source. However tropospheric noise is non-dispersive at microwave frequencies and therefore cannot be reduced or cancelled as plasma noise. Up to ~ 90% of the tropospheric path delay is due to the dry, or homogenous, part of the troposphere. The dry zenith path delay can be as large as ~ 2 m but the frequency drift on range rate measurements is essentially a geometric effect due to elevation changes (causing a time-varying path delay) during a tracking pass, typically ~ 6 hours long for deep space tracking. The induced Doppler signal amounts to ~ 1 mm/s, corresponding to 100 mHz at X-band and 400 mHz at Ka-band, but is easily accounted for with suitable elevation models and ground readings of meteorological data. On the opposite, the wet path delay amounts to only a few centimetres, but its fluctuations are hardly predictable because of the non-homogenous distribution of the water vapour. For these reasons wet path delay variations are much more difficult to be calibrated.

In order to meet the stringent requirements of Cassini GWEs, JPL developed a new class of ultra stable microwave radiometers (MWR) for the high accuracy calibration of the wet tropospheric noise. The MWR infers the wet tropospheric path delay from measurements of the sky brightness temperature T_b along the line of sight. MWRs are part of JPL's Advanced Media Calibration (AMC) system, comprising digital pressure sensors and microwave temperature profilers [6,7]. Figure 2 shows the drift due to the dry troposphere (on the left) and the high frequency noise due scintillation of N_{wet} (right side). The two plots derive from measurements of the path delay carried out by the AMC system on DOY 332/2001 at Goldstone complex, California. A statistical assessment of AMC readings singled out that, on average, the tropospheric noise level during SCE1 was about three times larger than the corresponding one during GWE1. This is due to the different season and tracking time of the two experiments: GWE1 tracking occurred on winter night times, when the tropospheric turbulence was at a minimum, while SCE1 took place in summer daytime, when convection-driven turbulence is at the peak. Since we don't have a larger data set to better characterize seasonal variations, we have modelled the wet troposphere with a sinusoidal trend having annual periodicity and an Allan deviation ~ $6.5 \cdot 10^{-14}$ at 60 integration time, with an upper bound of ~ 10^{-13}. Despite of the partially stochastic nature of the tropospheric noise and the highly dependence from the station location, we have found this simple model can be applied also to ESA's tracking station as an acceptable approximation.

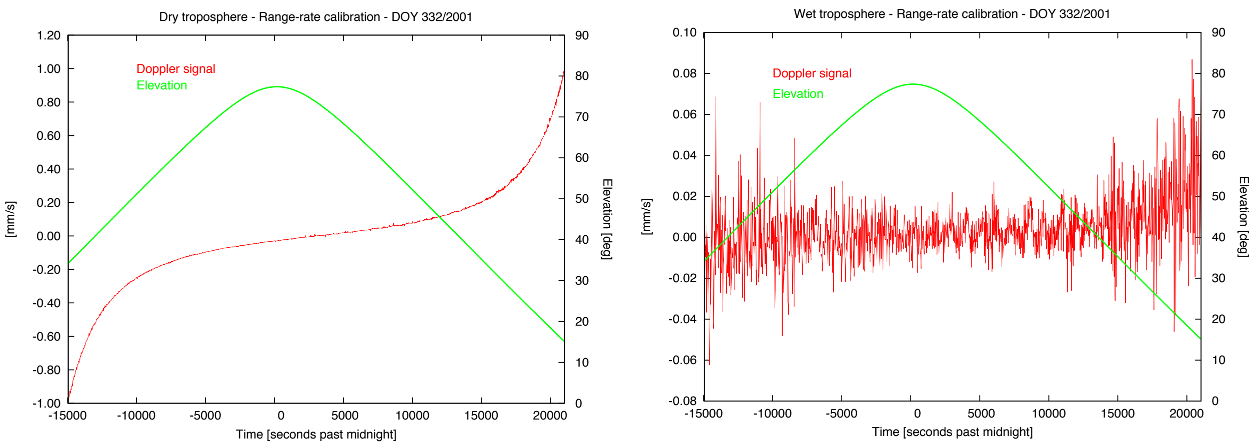

Figure 2: Dry and wet tropospheric frequency shift measured by JPL's AMC at Goldstone, California, on DOY 332/2001, during Cassini Gravitational Wave Experiment (GWE1). Tracking occurred during the night and time is expressed in seconds past midnight. Both uplink and downlink contribution is accounted for in the total range rate error.

The AMC system has been used mostly for radio science and gravity experiments. Most of tropospheric calibrations for Cassini tour data relay on standard GPS-based calibrations. However a closer look at Rosetta residuals reveals that they are somewhat noisier than Cassini ones (visible when plasma noise is not dominating). In order to understand the reason of this result, we fitted the Rosetta's sky frequencies with a six-parameter model (hereby "6 parameter fit" or simply 6PF):

$$f_r = x_1 + x_2 \cdot t + (x_3 + x_4 \cdot t)\sin(\omega_e t) + (x_5 + x_6 \cdot t)\cos(\omega_e t) \tag{3}$$

where ω_e is the Earth angular rotation rate and f_r is the frequency received at the ground antenna feed (i.e. the sky frequency). The six coefficients account for the geocentric slant range rate of the spacecraft (x_1 and x_2) and for both the Earth rotation and a slow spacecraft angular motion (x_3, x_4, x_5 and x_6). Provided that thruster firings or orbital maneuvers do not occur during a tracking pass, this model is quite accurate for a short arc fit during an interplanetary transfer phase. Near solar conjunction at SEP < 20°, where plasma noise dominates, the value of the Allan deviation at 60 s integration time of both 6PF and Doppler residuals is almost the same. At all other SEP angles the 6PF post fit residuals are ~ 20% less noisy and do not show any signature. This excluded unmodeled acceleration from the S/C attitude and other mismodeled forces in the dynamical model used to fit Rosetta data. In addition, this difference vanished at larger integration times, providing an indication that a relevant amount of noise was introduced by the computation of the model (predicted) observables.

Further investigations showed that numerical noise introduced by orbit determination codes plays an important role both for Rosetta and Cassini. Indeed orbit determination (OD) codes used by ESA

(AMFIN) and JPL (ODP) are both based on the mathematical formulation of Moyer [8,9]. Numerical noise stems from truncation and round off errors in the algorithm of computed observables (in particular when solving the light time problem in the general relativistic frame) and shows up in range rate residuals. Its source resides in the finite representation of time and distance variables and is a common problem in floating-point arithmetic. For a double precision number with 64 bit word, only 52 bits are used for the mantissa and the resulting ε (machine epsilon), giving the maximum relative error, is about 1.1×10^{-16}. This corresponds to ~ 0.15 mm range error at 10 AU. Noise on range rate measurements arises because they are computed essentially as a range differenced over a certain count time T_c. Numerical noise is therefore inversely proportional to T_c and, roughly speaking, to the projection of the relative velocity between the spacecraft and the Earth along the line of sight. An in depth analysis of how numerical noise affects range rate measurements is given in [10].

The finite SNR of electronic devices on both the ground and spacecraft equipment induce phase instabilities on the signal carrier. For space navigation two-way measurements are preferred because of the high frequency stability of the hydrogen masers used in the Frequency and Timing Subsystem (FTS) of the ground stations (Allan deviations are about 10^{-15} at 1000 s integration times). As a comparison, onboard Ultra Stable Oscillators (USO) have a two orders of magnitude worse stability (~ 10^{-13} at 1000 s) [11].

The main contribution from electronic systems comes generally from the onboard deep space transponders (DSTs), unless special design is adopted (as for Juno and BepiColombo Ka/Ka radio science transponder). These devices usually exhibit a white phase noise ($S(y) \propto f^2$) at frequencies larger than $10^{-4} \div 10^{-3}$ Hz. Rosetta's DST (a first generation digital device) exhibits a relatively poor frequency stability, with Allan deviations $\sigma_y \approx 4.7 \cdot 10^{-14}$, or 0.015 mm/s range rate accuracy, at 60 s integration time. For comparison, Cassini's analog DST performs better ($\sigma_y \approx 1.8 \cdot 10^{-14}$ or 0.006 mm/s at the same integration time).

A significant contribution to the overall Doppler error budget comes from thermal and mechanical deformations of the ground antennas. These deformations are caused by wind and gravitational loading, and time-varying thermal gradients across the antenna structure. An analysis performed by ESA showed that antenna mechanical noise at ESTRACK antennas is at level of ~ $1.6 \cdot 10^{-14}$ (0.05 mm/s) at 60 s integration time [12]. We assumed the same noise level applies also to 34m DSN stations.

The end-to-end noise on range rate observables is obtained by RSS (root sum square) of all random contributions. Systematic noises are assumed to be negligible in the band of interest for deep space navigation (from 1 to 10^3 s of integration time). The resulting model has been validated against available X-band range rate residuals from Cassini and Rosetta, for a total of 7 years of data at different epochs and heliocentric distances (see Figure 3 and Figure 4). In the Rosetta case the curve representing tropospheric noise has been shifted to take into account tracking from ESTRACK DSA2 station at New Norcia (Australia) in the southern hemisphere, while Cassini residuals refer to the DSN complexes of Goldstone (California) and Robledo (Spain) in the north hemisphere. We found that, on average, the predicted and the observed noise are in excellent agreement for both missions, confirming that meeting the 0.01 mm/s range rate accuracy at 60 s integration time requires the abatement of three error sources: plasma noise, noise from wet troposphere and numerical noise generated in the OD software.

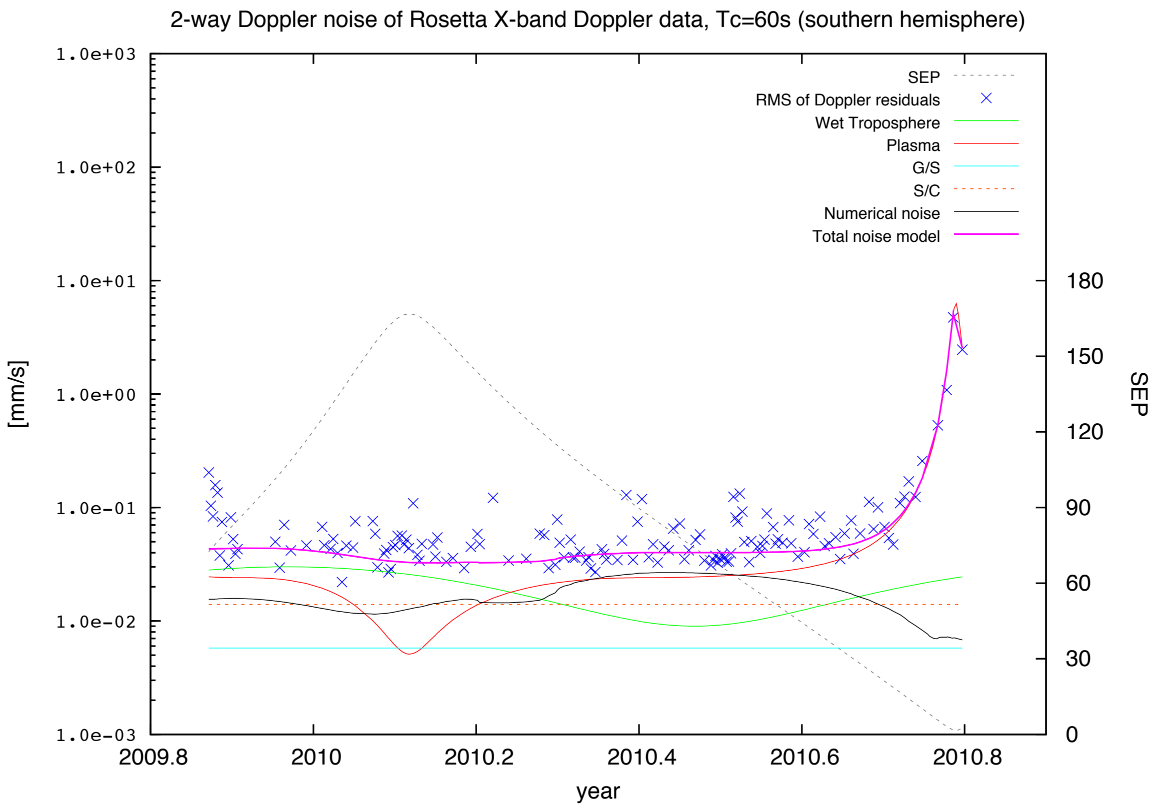

Figure 3: Comparison between error models and noise on Rosetta Doppler data. Blue crosses are the RMS values of Doppler residuals over a single tracking pass. The various curves are the models associated to the main noise sources (see legend).

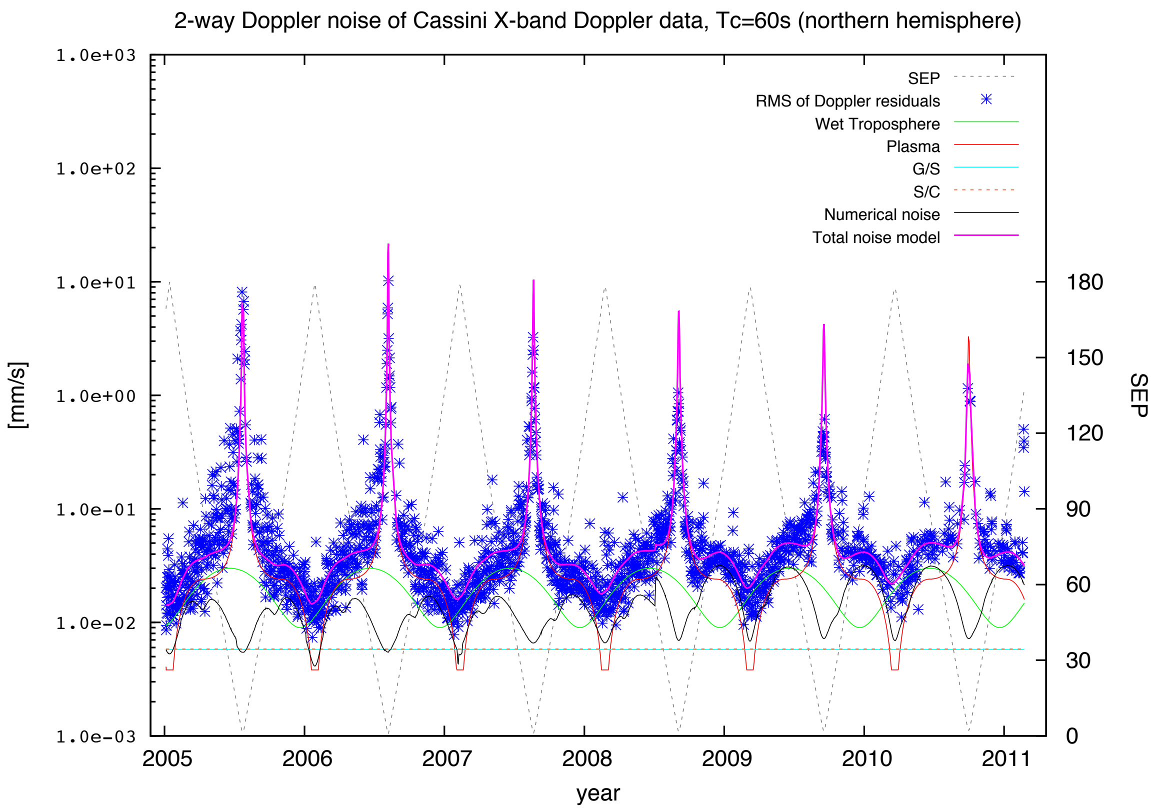

Figure 4: Same as in fig. 3, but for Cassini Doppler data.

IMPROVING DOPPLER TRACKING SYSTEMS

The most prominent noise source in the current X-band tracking systems has been identified in charged particle effects, mostly in interplanetary plasma. Solar wind plasma is responsible for the strong SEP dependence and is by far the dominant source as the spacecraft approaches solar conjunctions. The dispersive nature of plasma noise makes its mitigation relatively straightforward. Replacing a X-band with a Ka-band system will immediately reduce plasma noise by a factor of ~ 17 in terms of Allan deviation[1] at all solar elongation angles. However this remedy is still unsatisfactory when the signal propagates deep in the solar corona (SEP < 10°).

As shown by Cassini [1][2][3], the almost complete cancellation of plasma noise at nearly all SEP angles can be achieved by adopting a multi-frequency radio system. In this configuration the ground station simultaneously transmits two uplink carriers at X and Ka-band that are coherently retransmitted to ground by means of the on-board transponder to form a triple downlink (X/X, X/Ka and Ka/Ka). This configuration allows solving separately for the uplink and downlink Doppler shifts due to charged particles and for a dispersion-free component, containing the orbital Doppler shift. The plasma compensation scheme is effective in the approximation of the geometric optics. Diffraction and physical optics effects limit its applicability to impact parameters larger than few solar radii (5 to 6) [2]. The multi-frequency link has been used in the test of the general relativity carried out with the Cassini spacecraft in 2002 [2]. This configuration will be used also for the MORE radio science experiment of the ESA's mission BepiColombo to Mercury [13]. With a multi-frequency radio link Doppler observables become virtually independent from the solar elongation angle, thus providing range rate accuracies of 0.01 mm/s or less up to SEP of about ≈ 3° (see Fig. 5).

Currently, only the DSS-25 34m BWG antenna of NASA's Deep Space Network (DSN) complex in Goldstone (California) is equipped with Ka-band uplink and downlink capabilities. This station will support Juno's and possibly also BepiColombo precision radio science experiments [13]. Upgrading a ground station to Ka-band uplink requires not only the installation of Ka-band amplifier, feed and RF optics, but also the use of different feeds for the uplink and downlink signals to account for aberration effects. Although the technology already exists, the integration of a Ka-band dichroic for beam squinting (thus allowing for a separate Ka-band transmission feed) may require a massive redesign if the station was not specifically built with the possibility of a future upgrade to Ka-band transmission. ESA's most recent ESTRACK antennas (DSA2 in Spain and DSA3 in Argentina) have been designed for Ka-band transmit capability. An upgrade would therefore require a relatively short down time.

In the single link configuration, the only modification required from the spacecraft side is the support for a Ka-band uplink channel. Such capability is already available in digital transponder used in radio science experiment payloads [13]. In the case of a multi-frequency link the on board TT&C upgrade will be much more challenging. It entails the development of a new class of deep space transponders supporting simultaneously X/X, X/Ka and Ka/Ka radio links. Designing such integrated unit would be demanding from the point of view of electromagnetic compatibility. Use of typical radio science experiments configuration, were the standard X/X/Ka DST is used in conjunction with a dedicated Ka/Ka transponder, is an option. However, both configurations have a major drawback in the increased mass and power requirements of the onboard radio system, especially in the case of separate transponders if redundancy is needed for all units.

---

[1] This is valid for a 2-way observables and include the effect of the different uplink and downlink frequencies, assuming respectively 7.2 GHz/8.4 GHz at X-band, and 34.4 GHz/32 GHz at Ka-band.

The noise caused by the wet troposphere is a major contributor for SEP angles > ~ 60° and would become dominant also at smaller SEP angles if plasma noise were drastically reduced. Given its non-dispersive nature, a significant reduction of tropospheric noise requires the use of dedicated hardware and software at the ground station. The Doppler shift due to the variable content of water vapor in the Earth's troposphere can be inferred from MVR measurements of the sky brightness temperature along the line-of-sight. Off-the shelf radiometers developed for atmospheric profiling can be used for this purpose. This kind of instrument has different channels including the water vapor region of the spectrum (20-30 GHz) and allows calibrating up to 80% of the wet delay and its time variations at required integration times [14]. Better performances can be obtained by adopting an advanced, ultra-stable MWR. The custom design shall bear a larger dish with a narrow beamwidth (about 1 degree) and high side lobes suppression. This allows overcoming the tracking limitation of commercial radiometers especially at low elevation angles and close to the Sun. Also the receiver should be improved for rejection of internal noise sources (e.g. using Dicke switch technology) in order to meet the tighter Allan deviation requirements at both short and long time scales. A dedicated pointing control system will also be needed to track the spacecraft with an accuracy of about 0.01 degrees. However, since radiometers have intrinsic limitations that prevent their use in adverse conditions (e.g. heavy rain and fully cloudy sky), a backup system based on GNSS data should be always deployed at ground complexes, even if its accuracy is significantly worse, especially at short timescales.

The improvement of range rate observables would be vanished if not accompanied by a corresponding reduction of the numerical noise. The most effective and straightforward solution is the recompilation of the entire OD code in quadruple precision (QP). The expected reduction of the numerical error is about a factor of 100, but it comes at the cost of a much longer computational time. This solution appears incompatible with the need of quick updates of orbital solutions and near real time operations. The QP approach is best suited for science applications and non-operational scenarios (e.g. the final reconstruction of the spacecraft orbit for delivery to investigators), and in all situations where time constraints are not critical. A second possible solution entails a modified representation of all time variables. A simple approach would involve the use of two double precision words to store the integer and the fractional part of a time instant past a reference epoch (although other implementations are possible). Object-oriented programming capabilities can be exploited to overload mathematical operations involving any time variables without the need of extensive modification of the existing codes. This approach can reduce numerical noise by a factor of 10 at least, with a limited impact on the computational time. However, it would require a significant effort in terms of testing and certification of the software.

Noise contributions due to the frequency standard and electronics of the ground station are usually negligible. This statement is true also for the last generation of digital transponders. Thermo-mechanical noise appears a much more fundamental limitation to the improvement of Doppler systems. While today the ground antennas' thermo-mechanical stability is well below other noise sources, a top performance system would certainly require a reduction of this noise contribution. In a scenario where multi-frequency links, advanced MWR and improved OD codes are available, the end-to-end error budget would be limited by antenna mechanical noise. As proposed in [15], antenna mechanical noise can be effectively suppressed by means of a multi-station tracking configuration. In this approach a small listen-only antenna (operating in 3-way mode) tracks the spacecraft simultaneously with a larger deep space antenna (operating in 2-way mode). A proper linear combination of the 2-way data from the large antenna and the 3-way data from the small antenna provides a new observable which corresponds to the same orbital Doppler shift measured by the large, 2-way antenna, but has the mechanical noise from the small, and thus much stiffer, antenna. With a 3-5 m antenna the reduction of the mechanical noise would be quite significant, provided that the SNR is adequate for a correct recovery of the signal. This technique has been successfully tested, as proof-of-concept, using the DSS-14 (70m) and DSS-25 (34m) antennas of the DSN complex at Goldstone. During the test the sub-reflector of the larger antenna was deliberately moved along the line of sight to simulate a buffeting of the antenna. A drawback of this approach is that clock noise of the two antennas adds up. It is therefore mandatory that also the reference signal of the small antenna be generated by a highly stable H-maser.

The thermoelastic stability of the spacecraft antenna is usually not critical due the relatively small size (the largest reflector flying onboard a deep space mission is the 4m diameter Cassini HGA. However, in some mission scenarios where large temperature variations are expected (as in the Case of BepiColombo at Mercury), deformations of the antenna may become a non-negligible noise source.

Figure 5 shows the end-to-end range rate noise to be expected for two configurations of a future tracking system, as compared to the actual system. The figure refers to the Cassini case but similar results are obtained for Rosetta. The first configuration (red curve) is based upon a single Ka/Ka link that effectively reduces plasma noise over a broad range of SEP angles. It is assumed that a commercial MWR provides calibrations of the wet troposphere accurate to 80%. Such a system could be implemented in a rather straightforward way at ESTRACK antennas and would require a dual uplink, dual downlink, X/X+Ka/Ka onboard transponder. The range rate noise would be at 0.01 mm/s over a broad range of solar elongation angles.

Better performances are obtained with a combination of multi-frequency and advanced MWR providing 90% calibration of the wet troposphere (green curve). In this configuration it is also assumed that ground antenna mechanical noise is abated by ~ 60% by using multi-station tracking. In both scenarios we assumed the numerical noise has been reduced by about a factor of 10 by improved time representation in OD codes, the only solution suitable for real-time operations. It is noteworthy that in the best configuration the target accuracy is met also at very small SEP angles and the average upper limit to Doppler noise decreases to about 6×10^{-3} mm/s at 60 s integration time, corresponding to a 10-50 factor of improvement over current X-band system.

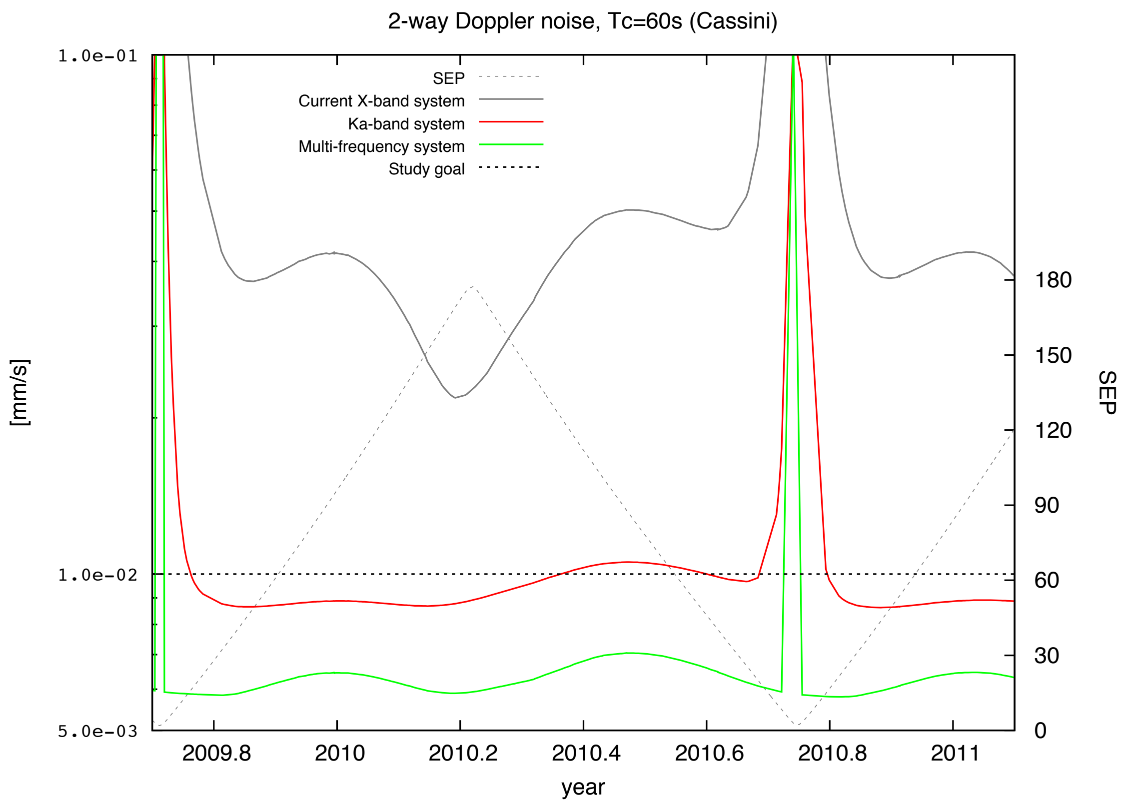

Figure 5: Expected noise in advanced Doppler systems. Red curve: coherent two-way Ka-band radio link and 80% calibration of the wet troposphere by using a commercial MWR. Green curve: multi-frequency radio link (X/X+X/Ka+Ka/Ka), 90% calibration of the wet troposphere by means of an advanced MWR, and 60% reduction of ground antenna mechanical noise by means of multi-station tracking. A reduced numerical (by a factor 10) is assumed in both configurations.

REFERENCES

1. Asmar, S. W., Armstrong, J. W., Iess, L. and Tortora, P. 'Spacecraft Doppler Tracking: Noise Budget and accuracy achievable in precision radio science observations'. *Radio Science*, vol. 40, no. RS2001, 2005 Doi:10.1029/2004RS003101
2. Tortora, P., L. Iess, J. J. Bordi, J. E. Ekelund, and D. C. Roth, 'Precise Cassini navigation during solar conjunctions through multifrequency plasma calibrations', *J. Guidance Navigation Control*, no. 2 vol. 27, pp 251–257
3. Bertotti, B., Iess, L. and Tortora, P. 'A Test of General Relativity using Radio Links with Cassini Spacecraft', *Nature*, no. 425: pp. 374–376, Sep 2003. doi:10.1038/nature01997
4. Armstrong, J. W., Iess, L., Tortora, P., Bertotti, B., 'Stochastic gravitational wave background: Upper limit in the 10^{-6} – 10^{-3} Hz band', *Astrophys. J.*, 599, 806-813, 2003
5. Iess, L., Dobrowolny, M., Bertotti B., 'Plasma effects on Doppler measurements of interplanetary spacecraft', *Astronomy and Astrophysics*, 121, 203-210, 1983
6. Naudet, C., Jacobs, C., Keihm, S., Lanyi, G., Linfield, R., Resch, G., Riley, L., Rosenberg, H., Tanner, A., 'The Media Calibration System for Cassini Radio Science: Part I', TMO Progress Report 42-143 Nov. 2000
7. Resch, G. M., Clark, J. E., Keihm, S. J., Lanyi, G. E., Naudet, C. J., Riley, A. L., Rosemnberg, H. W., Tanner, A. B., 'The Media Calibration System for Cassini Radio Science: Part II', TMO Progress Report 42-145 May 2001

8. Moyer, T. D., ‘Mathematical formulation of the double-precision orbit determination program (DPODP)’. Tech Rep.32-1527, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 1971
9. Moyer, T. D., ‘Formulation for Observed and Computed Values of Deep Space Network Data Types for Navigation’. Tech Rep.32-1527, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 1971
10. Zannoni, M. and Tortora, P., ‘Numerical Error in Interplanetary Orbit Determination Software’, submitted to *Journal of Guidance, Control, and Dynamics*
11. Asmar, S.W., ‘Characteristic Trends of Ultrastable Oscillators for Radio Science Experiments’, TDA Progress Report 42-129 (May 15, 1997)
12. Technical Note: ‘Allan Deviation Analysis for ESA DSA2 X/Ka Antenna’ by SED Systems Revision 1 December 2003
13. Iess, L. and Boscagli, G., ‘Advanced radio science instrumentation for the mission BepiColombo to Mercury’, *Planetary and Space Science* 49, 1597-1608, 2001
14. Nörenberg, D., Crewell, S., Löhnert, U., Rose, Th., Martellucci, A., “A novel ground-based microwave radiometer for high precision atmospheric observations between 10 and 90 GHz”, IEEE International Geoscience and Remote Sensing Symposium, Boston, Massachusetts, USA, 6-11 July, 2008
15. Armstrong, J.W., Estabrook, F.B., Asmar, S.W., Iess, L., Tortora, P., “Reducing antenna mechanical noise in precision Doppler tracking”, IPN Prog. Rep., 42–165, 15 May (2006)