POTENTIALS OF RADAR SPECKLE TRACKING IN INSTANTANEOUS ROTATION RATE AND RELATED PLANETARY PROPERTIES. Igor V. Holin, Kravchenko str. 12-244 Moscow 119331 Russia (holiniv@gmail.com).

Introduction: Apart from gravitational and magnetic fields that exist near the planet only and whose investigation needs the use of slow and expensive spacecraft, the radar fields scattered by rotating planets are formed very quickly near Earth and can be investigated by Earth-based radio systems. The exclusiveness of the radar field is that it potentially contains very accurate information about the short-term spin dynamics of the target planet closely related to its core-mantle-crust-atmosphere properties and evolution.

To account for short-term variations, the rotation of a planet can be characterized by the instantaneous spin-vector of its crust-mantle $\mathbf{\Omega}(t)$. Here I consider nearly instantaneous Earth-based radar measurements to a relative precision up to ~ 10^{-8}. The measurement technique was originally synthesized and analyzed from the Huygens-Fresnel principle using a statistical decision theory [1], [2].

Radar speckle tracking: The optimum measurement technique was shown to be speckle tracking [2]. It employs a phenomenon of moving speckles (speckle displacement) known long ago [3]. Moving speckles allow very accurate measurements of planetary rotation primarily due to a very small diffraction-limited speckle size. In radar astronomy speckle tracking measures the transverse (with respect to the line-of-sight *OZ*) *XY* component $\mathbf{\Omega}_{XY}(t)$ of $\mathbf{\Omega}(t)$. For example, the Manasse-Green technique (MGT) [4] calculates the absolute value and orientation of $\mathbf{\Omega}_{XY}(t)$ from the time delays of speckle displacement over several crossed baselines. Based on "frozen" speckle displacement over thousands of kilometers, the Holin technique (HT) [1], [2] uses the rotation of Earth and a substantially longer baseline comparable to the Earth radius that lead in together to a precision orders of magnitude better. Like MGT, HT calculates the absolute value of $\mathbf{\Omega}_{XY}(t)$ from the time delay. Unlike MGT, HT calculates the orientation of $\mathbf{\Omega}_{XY}(t)$ from the orientation of the baseline when it coincides with the speckle displacement direction or, equivalently, from the epoch of their coincidence.

There exist at least five ways that can be used in together and lead to further orders-of-magnitude improvement in the measurement precision relatively to the results of [5]. First, the experimental rms σ in $\Omega_{XY}(t)$ in [5] is about an order of magnitude larger than the minimum attainable standard deviation σ_0. Second, more than one receiving baseline can be used during a day, i.e. multiple baseline speckle tracking. Third, in appropriate cases (e.g., for Venus) the total transmission power can be used much more effectively when the transmission spectrum contains many frequencies, i.e. with multi-frequency speckle tracking [6], [7]. Fourth, the use of more than one transmission station, i.e. multi-source speckle tracking. Fifth, the increase in the total transmission power at each station.

Objectively, HT precision in the absolute value $\Omega_{XY}(t)$ of $\mathbf{\Omega}_{XY}(t)$ can be characterized by the Cramer-Rao lower bound (CRLB) that is the minimum attainable variance [8]. Because the attainability condition is satisfied [7], I calculate one-experiment relative CRLB σ_0^2 in $\Omega_{XY}(t)$ and compare it with the results of [5]. In addition to system noise [2], [8], the analysis accounts for signal incoherence characterized by the correlation coefficient *r* [6], [7], [9].

Mercury: Variations in Mercury's rotation rate relate to its main interior properties, such as the shape and extent of the crust-mantle, viscosity of the outer core, core-mantle interactions, the presence and properties of an inner core and so on. To conclude about most of them, a precision on the order ~ 10^{-7} and better is desirable.

After substituting a sum of mutually independent system and incoherence noises into Eqs. (56b), (57) of [8], I find for the Goldstone / Goldstone – Green Bank (G/G–GB) one-baseline radar interferometer σ_0 ~ 2.5×10^{-6}. A 27-baseline interferometer Goldstone/Very Large Array – Green Bank (G/VLA–GB) has $\sigma_0 \sim 10^{-6}$. Future prospects may relate, for example, to a fully steerable ~ 1 MW, ~ 100 m planetary radar (R) with the radar potential an order of magnitude higher against that of DSS-14 (~ 0.45 MW, 70 m) and two antenna arrays A1 and A2 separated by ~ 2000 km consisting each of 25 antennas (~ 35 meters in diameter) that form 625 long baselines. Then, R/R–GB, G/A1–A2, and R/A1–A2 would have one-experiment σ_0 ~ 10^{-6}, ~ 2×10^{-7} and ~ 10^{-7} respectively. For a 59-day rotation of Mercury, G/VLA–GB can measure the 88-day libration amplitude $\varphi_M \sim 2\times10^{-4}$ of its crust-mantle to $\delta_M <$ 1% after several experiments because $(88/59)\sigma_0/\varphi_M \sim 10^{-2}$. The 88-day libration that consists of several harmonics (88-day, 44-day and so on) can be constrained by G/VLA–GB to within ~ 1% – 0.1% during several years. The presence and parameters of free libration can be estimated as well. For example, the amplitude of ~ 12-year free libration can be measured with G/VLA–GB during several years to ~ 2 arcseconds. With R/A1–A2 these values should be an order of magnitude better.

However, the reported relative one-experiment rms in $\Omega_{XY}(t)$ is $\sigma \sim 2\times10^{-5}$ (G/G–GB) that resulted after 35 experiments in $\delta_M \sim 5\%$ [5]. Any interpretation can be conclusive within this precision only that leaves most of the fundamental properties of Mercury out of reach. The authors of [5] tried to justify their results through a non-CRLB analysis Eq. (A6) but it leads to $\sigma_x \sim 5\times10^{-5}$, which is inconsistent with their own experimental σ ($\sigma_x/\sigma \sim 2.5$). The experiments in [5] are far from CRLB ($\sigma/\sigma_0 \sim 8$) and can be referred to as non-CRLB experiments. This argues that both theoretical and experimental results in [5] mislead about objective HT potentials.

Venus: Besides the interior, variations in the rotation rate of Venus's crust-mantle may relate to a dense atmosphere. Like Mercury, a precision on the order ~ 10^{-7} and better is needed. Unlike Mercury, this precision should be reached within several hours or so because short-term "atmospheric" variations can be substantially stochastic.

To account for incoherence from Venus's atmosphere, I approve $r \sim 0.5$ and $r \sim 0.9$ for the 3.5 cm and 13 cm wavelengths respectively and find one-experiment $\sigma_0 \sim 2\times10^{-6}$ for G/G–GB and ~ 4×10^{-7} for A/VLA–GB (G/VLA–GB). Multi-frequency (m) G/G–GB (mG/G–GB) and mA/VLA–GB have $\sigma_0 \sim 2\times10^{-7}$ and $\sigma_0 \sim 10^{-7}$ respectively. When performed daily, these experiments allow studies of main variations in Venus rotation rate related to its interior and atmosphere [7]. A non-CRLB analysis Eq. (A6) in [5] gives for G/G–GB $\sigma_x \sim 10^{-5}$ ($\sigma_x/\sigma_0 \sim 5$).

Multi-frequency mG/A1–A2 and mA/A1–A2 (mR/A1–A2) would have $\sigma_0 \sim 3\times10^{-8}$ and ~ 1.5×10^{-8} respectively allowing studies of the full spectrum of short-term variations of Venus up to ~ 10^{-8}.

Europa: Like Mercury, any liquid layer inside Jupiter's moon Europa can separate the outer shell from the interior amplifying the main 3.5-day libration amplitude to $\varphi_E > 10^{-4}$. A non-CRLB analysis Eq. (A6) in [5] with $\sigma_x \sim 3\times10^{-4}$ requests tens G/G–GB experiments to detect a minimum value of $\varphi_E \sim 10^{-4}$. The CRLB analysis Eqs. (56b), (57) [8] gives $\sigma_0 \sim 5\times10^{-5}$ ($\sigma_x/\sigma_0 \sim 6$) that detects an ocean within one G/G–GB experiment (few hours) while ~ 25 experiments can measure any possible value of φ_E to $\delta_E \leq 10\%$. Same precision could be reached within one R/R–GB experiment for which $\sigma_0 \sim 10^{-5}$.

Discussion and conclusion: I have shown that the minimum attainable deviation (CRLB) in $\Omega_{XY}(t)$ is about an order of magnitude better than the experimental rms in [5]. This means that HT was used to about ~ 10% of its potential while the precision losses are as large as ~ 90%. Because the resulting rms is proportional to a square root of the total number of the experiments, the authors of [5] instead of one CRLB experiment that needs few hours (and, say, ~ 100 thousand USD) have to attract ~ 100 experiments (~ 10 million USD) for many years to obtain the same precision. In other words, the economic efficiency of non-CRLB experiments in [5] is about ~ 1% only. The experimental σ in [5] is comparable to that in spacecraft measurements [10], [11]. Because σ_0 is much smaller, radar should be better than spacecraft.

In spite of good agreement in the values for the 88-day libration amplitude [10], [11], which was first measured by HT that detected a liquid outer core [5], the rotation and related properties of Mercury remain substantially undetermined. The difference between the measured values of the mean rotation rate is ~ 1.2×10^{-6} comparable to their deviations from a resonant value while the reported precision is ~ 1.6×10^{-7} [10], [11]. No concrete conclusion can be made from here about how far is the measured rotation from a resonant value or about the presence and parameters of free libration.

The difference in the experimental estimates for the mean rotation rate of Venus exceeds ~ 10^{-5} [12] where the authors do not exclude large variations. In contrast, the authors of [13] argue for smaller variations and do not exclude measurement errors. In both cases, variations are discussed without measuring them.

In spite of many spacecraft missions, the measurements of the mean rotation rate of Mercury and Venus must remain inconclusive mainly because of the lack of the data on the full spectrum of spin rate variations that relate to fundamental planetary properties and can be obtained from Earth-based radar as shown in the above. A reasonable balance between radar and spacecraft can give space agencies a necessary flexibility to become much more effective and far-reaching in their deep space activity.

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