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Dear colleagues,

Scientific rationale for common frequency referencing at DORIS–GNSS co-locations

Please find below the scientific rationale for connecting co-located DORIS beacons and GNSS receivers to a common frequency reference, prepared in support of discussions with CNES on the future evolution of the DORIS ground network.

Yours sincerely,

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Summary: DORIS is intrinsically sensitive to the frequency transmitted by each ground beacon: the beacon oscillator is therefore part of the measurement model, not merely an element of station hardware. Short-term oscillator stability supports the precision of the Doppler measurement itself, whereas the mean frequency offset and slower variations over a satellite pass must be accounted for in orbit determination. If not independently known, these quantities are estimated from the same DORIS observations that determine the satellite orbit and geodetic parameters. Connecting a DORIS beacon and a co-located GNSS receiver to the same frequency reference makes this ground-frequency behaviour independently observable. The direct benefit is not merely one parameter fewer: it reduces a known ambiguity in the Doppler observation and preserves more information for orbit, station and Earth-orientation estimation [1–4,17–23].

The scientific case is supported by measurement physics, CNES/CLS real-data experiments and controlled long-term simulations. Existing experiments demonstrate improved formal observability, local orbit agreement, residuals and station-coordinate repeatability [1,2], while simulations show that pass-wise frequency-bias estimation can leave post-fit residuals almost unchanged while degrading recovered orbit and Earth-orientation information [4]. The effect is already present at low altitude and becomes more pronounced at higher altitudes. Common DORIS–GNSS frequency referencing is therefore relevant to the present DORIS constellation and

gains further importance for Genesis, while building on an already extensive DORIS–GNSS co-location infrastructure [3,5,6].

1. Frequency behaviour in the DORIS observation

The precise DORIS measurement is based on a one-way Doppler link. An error in the transmitted beacon frequency therefore appears in the same physical quantity as a change in beacon–satellite line-of-sight velocity. To first order [7,8,17],

$$\delta\dot{\rho} \approx c \cdot y, \quad \text{with } y = \frac{\Delta f}{f}$$

where $\delta\dot{\rho}$ is the apparent range-rate error, c is the speed of light, f is the transmitted carrier frequency, Δf is its error, and y is the fractional-frequency deviation. A fractional-frequency error of $1 \cdot 10^{-12}$ is equivalent to about 0.30 mm/s, or 3 mm over a 10 s Doppler count, directly comparable with the precision level of the DORIS observable [7,8,22,23].

The DORIS system design accordingly distinguishes oscillator behaviour by time scale [8]. Short-term stability concerns consecutive Doppler measurements; current CNES requirements specify better than $7.5 \cdot 10^{-13}$ over 10–100 s for third-generation and $1 \cdot 10^{-12}$ for fourth-generation beacons [7]. Of greater relevance to orbit determination is medium-term behaviour: slow frequency variations over the several minutes of a satellite pass. Unlike short-term fluctuations, these produce coherent Doppler signatures. CNES already identified such variations as particularly critical because the resulting velocity error can resemble orbit or beacon-position errors; a typical USO frequency slope of $2 \cdot 10^{-13}$ per minute was estimated to produce a positional error of approximately 4 cm over a SPOT pass [8].

Long-term drift, originally considered on time scales from a day to a month, can largely be accommodated because the mean beacon frequency is conventionally estimated during processing [8]. This, however, leads directly to the central estimation issue: satellite motion and beacon-frequency error both appear as frequency changes in the same observable. A pass-wise frequency parameter can therefore absorb signal that would otherwise constrain orbit, dynamic, station or Earth-orientation parameters [1,17,18,27]. Independently observing the ground-frequency behaviour reduces this intrinsic ambiguity.

2. Information provided by a common GNSS frequency reference

The role of a co-located GNSS receiver is complementary to that of the DORIS USO. The USO provides the short-term stability required for the Doppler measurement; GNSS can provide an independent observation of the common reference frequency and its evolution over longer intervals. The purpose is therefore not to replace or improve the intrinsic 10 s performance of the DORIS oscillator, but to make its mean frequency offset and pass-scale variations independently observable.

In precise point positioning (PPP), the receiver clock is estimated epoch by epoch from GNSS code and carrier-phase observations and consequently contains measurement noise, product errors, multipath and receiver-dependent effects [9,10]. A 5 mm phase-equivalent clock uncertainty corresponds to about 17 ps; differencing two independent epochs only 10 s apart would yield a fractional-frequency uncertainty of order $2 \cdot 10^{-12}$. A PPP clock is therefore not automatically a better short-term oscillator than the DORIS USO. Its value emerges over longer intervals, because the slope of the clock series,

$$y(t) \approx \frac{dx(t)}{dt} \approx \frac{\Delta f(t)}{f}$$

provides an independent estimate of oscillator frequency and slow evolution. Here, $x(t)$ is the GNSS receiver-clock offset with respect to the GNSS time scale, $y(t)$ is the fractional-frequency deviation of the common reference, f is the nominal reference frequency and $\Delta f(t)$ its deviation from nominal. Published PPP time-transfer results reach frequency stabilities around 10^{-13} at 100 s and a few 10^{-14} at 1000 s [9,10]. Constant clock or hardware offsets disappear in the temporal derivative; only time-variable delays need to be controlled.

3. Evidence from DORIS processing and simulation

CNES has already demonstrated the practical feasibility of this approach. In a Sentinel-3A experiment, GNSS ground-clock corrections sampled every 30 s were used instead of one DORIS frequency offset per pass. DORIS- and GPS-derived estimates of the common USO behaviour agreed at approximately the 10^{-12} level. Removing the pass-wise df/f estimation improved the formal observability of selected along-track dynamic parameters by about 42–53% and tropospheric-gradient parameters by about 10%; for the investigated Kourou and Hartebeesthoek passes, the mean local along-track difference to an independent GPS orbit improved from about –2.60 cm to –0.93 cm [1]. A 2026 CNES/CLS assessment of four clock-connected master beacons again found lower DORIS residuals and improved station-coordinate repeatability [2]. Independent studies of onboard USO behaviour likewise demonstrate that oscillator modelling errors can propagate into station coordinates and Earth-orientation parameters [11–16].

Controlled seven-year simulations provide the complementary network-level evidence [4]. Estimating one frequency bias per station and pass left standard post-fit statistics almost unchanged while increasing the recovered orbit RMS. The effect was already present at low altitude, mainly along-track, and became substantially stronger at higher altitudes, particularly in the cross-track and along-track components. At low altitude, pole-coordinate scatter increased by about 16–20%, while formal pole-coordinate precision degraded across the investigated orbit classes. Thus, an apparently satisfactory observation fit does not imply that geodetic information is unaffected.

4. Enabling DORIS phase processing

While a DORIS receiver measures phase, current POD and the generation of geodetic products use only Doppler, i.e. phase differences. The limited number of DORIS satellites does not allow for an epoch-wise estimation of beacon and satellite clock corrections. Processing of the phase measurements is therefore limited by the short- and long-term behaviour of the involved USOs [28], which are not sufficiently stable over longer time scales to allow straightforward phase processing. Operating a GNSS receiver from the beacon USO, and likewise operating the onboard GNSS receiver from the DORIS USO, as recommended for future DORIS missions, opens the potential to process DORIS phase observations. Optimally, this could be realised through joint processing of DORIS and GNSS, thereby strengthening the resulting solutions. This potential needs to be explored.

5. Relevance for Genesis and the ground network

Genesis is planned in a circular orbit at approximately 6,000 km altitude and 95° inclination [5,6], placing it in the higher-altitude, near-polar regime for which the simulations indicate increased sensitivity to pass-wise beacon-frequency estimation [4]. Genesis also applies the same metrological principle onboard by sharing a common frequency reference between DORIS and GNSS [5,6].

The ground network is already favourably positioned: in 2024, 51 of 61 DORIS sites were reported as co-located with GNSS [3]. A common reference at one beacon benefits every DORIS-equipped satellite observing that station, making the scientific return network-wide rather than mission-specific. Common-clock and time-coherence concepts are also increasingly used in geodetic metrology to expose technique-specific systematics and strengthen multi-technique combinations [5,24–26].

6. Recommendation

The measurement physics, DORIS system design, CNES/CLS experiments, published clock studies and independent simulations consistently support common DORIS–GNSS frequency referencing as a scientifically justified evolution of the ground network. Its principal value is to make the beacon frequency offset and medium-term, pass-scale evolution independently observable and thereby reduce the need for empirical frequency parameters estimated from the same observations used for precise orbit and geodetic determination. In addition, independent clock information offers the potential to exploit DORIS carrier-phase observations more directly and thereby further strengthen future DORIS solutions.

It is therefore recommended that a common, observable DORIS–GNSS frequency reference be adopted as a standard objective for new DORIS installations and major renovations at GNSS-co-located sites, with progressive extension to existing co-locations where technically feasible. The present beacon oscillator performance requirements should be retained. In processing, the independent GNSS-derived frequency information can be

applied as a correction or constraint, while conventional pass-wise estimation remains available as an operational fallback. For future DORIS missions, DORIS and GNSS should likewise be operated from a common onboard frequency reference, as also recommended by the Copernicus POD Quality Working Group, to support improved clock characterisation and future DORIS phase processing. This preserves the robustness of the established DORIS system while removing an avoidable ambiguity from its highest-precision scientific use and opening additional potential for future processing strategies.

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