GAlileo Survey of Transient Objects Network (GASTON) Project

Searching Dark Matter using the Galileo Satellites

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***Abstract*— Some models for Dark Matter (DM) suggest possible encounters with a period τ of macroscopic dark structures with the Earth, implying transient signatures on clocks onboard GNSS satellites. In this paper we first introduce the *GASTON* project, an original study dedicated to the search for such 'DM transients' using the network of passive H-Maser onboard Galileo satellites. This project is based on a 3-months measurements campaign carried out in the early 2021 where precise satellite clock measurements are supplemented by an intensive laser ranging (SLR) campaign on Galileo satellites. Then, we present preliminary results based on single satellite frequency jumps between consecutive 30s epochs over the 3 months campaign. In particular, we already bring strong constraints on the parameter space for transient DM objects from 10^5 to 10^9 km, a region which was never explored previously with GNSS clocks.**

Keywords—Fundamental physics test; Galileo constellation; Dark matter; fundamental constants.

I. Introduction

How may a constant vary? This question seems semantically absurd. However, it turns out to be of prime importance in the quest of unknown physics beyond the current theoretical models. Indeed, fundamental constants are free parameters inherent to the theory that introduces them. Therefore, a physical quantity may be qualified as constant in space and time only within a given theoretical framework, i.e. the Standard Model (SM) in particle physics and General Relativity (GR) according to our current knowledge. Therefore, a hypothetical variation of physical quantities which are supposed to be constant in the SM or the GR could reveal some failure of these models, or equivalently, could be the discovery of new physics beyond these models [1,2].

Currently, the SM is described by an amount of 22 fundamental constants determined by the experiment. For example, the reduced Planck constant $\hbar$, the elementary charge e, the speed of light c, the rest mass of particles m_p (proton), m_e (electron), m_q (light quarks), etc. Their absolute value depends on a given system of units. However, in practice, a physical measurement of these constants is a comparison of two quantities. Subsequently dimensionless combinations of constants are measured, called *fundamental parameters*.

The purpose of our project is to exploit the capabilities of the Galileo constellation to test fundamental parameters, either through transient (in time) effect or through space variation of these parameters. In this paper we will focus only on the test of two fundamental parameters: the fine structure constant and the proton-to-electron mass ratio. Notice that other fundamental parameters could also be tested, based for example on the light quarks mass. The fine structure constant, denoted by α, governs the strength of the electromagnetic interaction and results from the following combination of the fundamental constants e, c and $\hbar$ along with the dimensional parameter ε_0, i.e. the vacuum permittivity:

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar\, c} \approx \frac{1}{137}\,. \quad (1)$$

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The proton-to-electron mass ratio is denoted by μ such that:

$$\mu = \frac{m_\mathrm{p}}{m_\mathrm{e}} \approx 2000\,. \tag{2}$$

Our phenomenological approach is quite general in the sense that we are testing variation of fundamental parameters whatever the time transient or large-scale space variations of these parameters. Nevertheless, this paper relies on recently introduced dark matter models as a test bench of our method and limits the description of our analysis to transient effects no longer than 2 months. But it is important to keep in mind that the same analysis can also apply to long-term effects induced by large scale variations of the fundamental parameters. This last point will be described in a future paper.

Several astrophysical observations suggest that ordinary matter contributes only to around 5% to the total mass-energy content of our Universe. The unknown remaining part is commonly separated into the dark matter (DM) and the dark energy. Some theoretical models suggest that DM consists of a massive scalar field of which the feeble interaction with ordinary matter produces spacetime variations of fundamental constants (see [3-5] and references therein). Recently, a family of such DM models which describes clusters or classical structures of macroscopic size have gained tremendous interest. These structures arise naturally in astroparticle physics, or in cosmological models of grand unification and inflation. They are viable DM candidates that could regularly cross the Earth, hence the name of DM transients, and consist in the condensation of the scalar field into spatially extended objects like, e.g., the topological defects [6,7], nontopological solitons [8], dark clusters [9,10] or gravitationally bound particles into dark stars [11-13].

However, some parameters inherent to these models are poorly constrained for the moment: 1) the mean duration τ between two consecutive encounters of transients with the Earth, 2) the size *d* of the transient, 3) the interaction strength Λ between the DM and the ordinary matter, called the *coupling constant*. The 3-dimensional area in which the DM transient can be detectable in adequacy with a combination of these three parameters is called *the parameter space*. The ultimate goal is the direct detection of DM but the lack of experimental observation, in regions of the parameter space where transient objects can possibly exist, excludes some models.

During such hypothetical encounters, it has been shown in [6,7,13] that a variation of fundamental constants is possibly observable by means of precision measurement devices. In particular, if the trajectory of the Earth in the Galactic halo intercepts such (large enough) DM transient, two distant and initially synchronized identical clocks are expected to exhibit a distinct de-synchronization pattern when this transient is crossing them. Then, in our search for transient signatures, a geographically distributed network of atomic clocks like the GNSS constellations can be used to seek the synchronous propagation of clocks frequency "glitches" at galactic velocities throughout the network. This approach can be compared to the gravitational wave detection, where correlations between detectors are a strong indicator of a real event.

The previous searches for subsequent glitches of GPS clocks were restricted to data mining method on clock products only [6,13]. In this paper we present an original project dedicated to the search for such 'DM transients' using the network of passive H-Maser onboard Galileo satellites as a gigantic detector of 60000 km aperture. The novelty of this project is the combination of measurements (clocks and orbit products, Satellite Laser ranging (SLR)…) for the search for DM transients, with a special care to the systematic effects, during an especially dedicated 3-month campaign. In this paper we present preliminary results of this project due to their yet remarkable interest, offering a strong first reduction of the parameter space. And so, it excludes event configurations for which it is not useful to try to detect transients since we know that such events do not happen. The main result is a dramatic extension of the discovery range of DM transients with a sensitivity not reached so far with GNSS clocks. In particular, the area of transient size from 10^5 to 10^9 km was never explored for a so large encounter time τ (up to 2 months). The SI units are used throughout this paper.

II. Exploiting Galileo Constellation Capabilities

A. The GASTON Project

The final purpose of the GASTON (GAlileo Survey of Transient Objects Network) project is to explore some possibilities offered by the Galileo constellation to search for signatures of variations of fundamental parameters in the close neighborhood of the Earth. In that sense, it offers a considerable extension of the work of [6,14]. This project is based on a 3-months measurements campaign carried out in the early 2021 where precise satellite clock measurements are supplemented by an intensive SLR campaign on Galileo satellites. The Galileo constellation is well-suited to search for such DM transients because of the extremely stable passive H-maser clocks onboard satellites, because of the corner cubes allowing to perform SLR measurements and because of the number of satellites and of their spatial dispersion, allowing to exhibit distant correlations with the delay predicted by the trajectory of our Solar System within the DM halo. Another strong point of the GASTON project is the better theoretical modeling since we have considered a smooth profile for the DM transient (instead of a step function) derived from a specific Lagrangian formulation. In addition, we also consider for the first time the orbital motion of the satellites. This enables to extent the potential detection to any large DM objects, well beyond the size of the Earth, namely a strong improvement of the current literature dealing with the GPS constellation [6,14].

The GASTON project can be divided into two levels. First, the exclusion level which consists in constraining large regions of the parameter space by producing a first rough analysis. Besides the notable scientific interest of such exclusion, it offers the advantage to target the region of the parameter space where to seek a possible signature of DM transients. Then, the second level, that we call the "*detection level*" deals with an exhaustive correlation analysis over the whole set of available Galileo satellites. The purpose of this second step, still under investigation, is the direct detection of possible signatures of variation of fundamental constants or the derivation of a refined exclusion zone.

In this paper, we restrict our study to the first *exclusion level*. Although it must be considered as a preliminary result regarding the entire GASTON project, it already introduces a considerable improvement of the current constraints obtained with GPS clocks. In order to obtain these preliminary results, we have developed a simple method that we refer to as the *frequency jump* (which is also known as the *maximum reach analysis* in the literature) introduced in Section II.B.

B. The GASTON Model

Coupling the ordinary matter or electromagnetism to a (light) scalar field φ is motivated by some effective theories describing quantum gravity like string theory, see for example [1,2,4,5]. In this paper we choose more specifically a quadratic interaction between the scalar field and the standard matter [3,6,15], in order to conserve the maximum of symmetries of the Lagrangian. As an effective point of view, these models predict a space variation of the fundamental parameters defined in (1) and (2), according to the phenomenological model [2]:

$$\alpha_{\rm eff}(x) = \alpha_0 \left(1 + \frac{\hbar\, c}{\Lambda_\alpha^2}\varphi^2(x)\right), \tag{3}$$

where $\alpha_{\rm eff}$ is the measured *effective* fine structure constant, whereas:

$$m_{\rm f}^{\rm eff}(x) = m_{\rm f}^0 \left(1 + \frac{\hbar\, c}{\Lambda_{\rm f}^2}\varphi^2(x)\right), \tag{4}$$

are the *effective* fermion masses, leading subsequently to a coordinate dependence of the proton-to-electron mass ratio μ. The constants α_0 and $m_{\rm f}^0$ are respectively called the *bare* fine structure constant and the *bare* fermions mass. In equations (3) and (4), the coupling strength $\Lambda_{\rm x}$ quantifies the effect of the scalar field interaction on the electromagnetism (subscript α) or on the fermions mass (subscript f).

In this paper, we restrict the origin of possible variations of fundamental parameter to transient DM objects, and so only such models will be described here. Following numerous models, we suppose that the scalar field condensate into compact structures like topological defects, Q-balls, dark clusters or boson stars [6-13]. In that case, the apparent spacetime variation of the fundamental parameter (3) and (4) only occurs mainly inside the structure. Such structures are supposed to be DM candidates, fulfilling partially or totally the mass-energy budget devoted to DM in the Universe. Therefore, we require that the energy density averaged over these DM objects network cannot exceed the measured local DM density $\rho_{\rm DM}$ of 0.3 ± 0.1 GeV cm^{-3}. Notice that henceforth $\Lambda_{\rm x}$ quantifies the effect of DM on ordinary matter. In a fascinating perspective, these DM structures could regularly cross the Earth for specific configurations of the parameter space, hence their name: transient DM [6,7,10,13]. Such a hypothesis arouses interest for high precision measurements in the close vicinity of the Earth.

In this paper we assume a planar symmetry, with a scalar field depending only on the z-coordinate. We have chosen a hyperbolic tangent profile for the field $\varphi(z)$, such that:

$$\varphi(z) = V^2 \tanh\left(\frac{z}{d}\right), \tag{5}$$

where V^2 is the maximal amplitude of the scalar field (outside the transient) and d is commonly referred as to the transient size (although the φ^2 coupling varies significantly between -2d and +2d), also related to the mass of the scalar field. This choice is motivated by two reasons: 1) it corresponds to the simplest Domain Walls (DW) solution (in a tensor-scalar theory characterized by a quartic self-potential), which forms planar structures, as considered in [16,17] and 2) it is supposed to mimic the radial profile of more complex spherical or cylindrical structures for a radius d larger than the typical orbital radius of the Galileo constellation. Nevertheless, the quality of this approximation should be assessed on a case-by-case basis.

We consider more specifically the case addressed in [6,14] where a network of transients might take a part to the energy density $\rho_{\rm DM}$. The bound on the energy density per domain wall is reached in the extreme case where the total energy density averaged over the DW network fulfills $\rho_{\rm DM}$. Under this assumption, the amplitude of the scalar field outside the transient is given by:

$$V^2 = \frac{3}{4}\, v_{\rm gal}\, \tau\, d\, \rho_{DM}\,, \tag{6}$$

where $v_{\rm gal}$ is the typical transient velocity relative to the Earth. This result slightly differs from [6] since we consider in (5) a (more realistic) smooth solution rather than a step function.

Any space (and time) variation of the fundamental constants directly affects the stability of atomic clocks, thereby possibly leaving a measurable signature on Galileo H-Maser clock products. This enables to twist the Galileo constellation to transform it into a DM detector. Indeed, the shift in energy levels inside the DM transient implies a transient shift in atomic clock frequencies ω:

$$\frac{\omega(t)-\omega_0}{\omega_0} = K_\alpha \frac{\Delta\alpha(t)}{\alpha_0} + \sum_{\rm f} K_{\rm f} \frac{\Delta m_{\rm f}(t)}{m_0}, \tag{7}$$

where the sensitivity coefficients $K_{\rm x}$ are specific to the H-Masers and depend on the interaction x (electromagnetism α or fermions f) with: $K_\alpha = 4$ and $K_{\rm f} = 2$, see [18]. They relate in (7) the observable relative frequency variation in the left-hand side to the effective model of new physics in the right-hand side, which itself is related to the behaviour of the scalar field as depicted in (3-4).

C. The Frequency Jump Method

Before proceeding to a full correlation analysis among the Galileo clocks which will be presented in a future communication, we introduce the simple *frequency jump* method to obtain a first strong exclusion area of the parameters space. In this method, the smooth profile (5) is considered but the velocity of the spacecraft (S/C) is neglected, reducing the computing demand but in a same time allowing for the study of large transients. Then, we only consider the observed maximum frequency jump of each Galileo clock independently in comparison to a reference, during the 3 months campaign. The word "independently" means that in this first step, we do not correlate data from different satellites, and we do not consider the frequency evolution over several epochs.

Let us define by $s^a(t)$ the clock bias between a clock a and a reference clock r. In our analysis, we have arbitrarily chosen the reference clock r as the one onboard the Galileo satellite E01 while the other Galileo clocks a have been selected under the following conditions:

- Passive H-maser as the master clock.
- No signal interruption or orbital maneuver disturbing the frequency comparison during the 3-months campaign.

Then, considering a time sample Δt of 30s, we define the frequency difference between the reference and the clock a by comparing the phase with the previous epoch:

$$\Delta s^a(t) = s^a(t) - s^a(t - \Delta t)\,. \tag{8}$$

We use the word "frequency" keeping in mind that it is a misuse of language, the true relative frequency $\Delta f/f$ is obtained by dividing $\Delta s^a(t)$ by the time sample Δt and taking the limit of a vanishing Δt.

We detail here the case of large transients because it has never been dealt with the GNSS constellations. The symmetries inherent to spherical or cylindrical transient objects induce that the gradient of the scalar field is directed along the radial direction. Large transients can be dealt with similarly to domain wall when the radius of curvature is far larger than the orbital radius of Galileo satellites. Thus, the gradient of the scalar field is perpendicular to the quasi-planar surface of the transient object assimilated to a DW. Let us denote this direction $\boldsymbol{n}_\perp$ and the associated radial coordinate z of which the origin is at the core (symmetry center) of the transient. We consider the case where the orbital plane of the reference satellite E01 is parallel to the DW surface, thus normal to $\boldsymbol{n}_\perp$. In this case, the distance between the reference E01 and any clock a, projected onto $\boldsymbol{n}_\perp$ can never exceed $Lar_\perp$ = 25600 km, considering the angle between the orbital planes. The space gradient is limited by $Lar_\perp$, restricting the amplitude of the relative disturbance between the clock a and the reference r.

We denote by $v_\perp$ the transient relative velocity projected onto the direction $\boldsymbol{n}_\perp$. During the short interval Δt, the trajectory of the spacecraft can be neglected since our method consists in keeping the maximum frequency jump epoch by epoch, without regarding the past frequency evolution. Under these conditions the frequency $\Delta s^a(t)$ has the simple analytical form:

$$\Delta s^a = \hbar\, c\, \frac{dV}{\Lambda_\alpha^2\, v_\perp}\left(\Delta\varphi^a - \Delta\varphi^r\right)\,, \tag{9}$$

if the interaction with electromagnetism Λ_α is considered (and similarly the coupling constant $\Lambda_{e/p}$ takes part in (9) if the variation of the mass ratio μ is considered). In the above expression (9) and under the assumptions mentioned previously, the constant $\Delta\varphi^a$ relative to the initial position of the clock a and the distance covered by the transient reads:

$$\Delta\varphi^a = V\,\tanh\left(\frac{z_0^a + v_\perp\,\Delta t}{d}\right) - V\,\tanh\left(\frac{z_0^a}{d}\right). \tag{10}$$

Similarly, the constant $\Delta\varphi^r$ has the same expression, replacing the superscript a by r. Making the assumption that the $\boldsymbol{n}_\perp$ projected distance between any Galileo satellite a and the reference r cannot exceed $Lar_\perp$ during the transit of the large transient, we define as an extremum value

$$z_0^a = z_0 - \frac{1}{2}L_{ar\perp}\,, \tag{11}$$

for the initial position of the clock a, and:

$$z_0^r = z_0 + \frac{1}{2}L_{ar\perp}\,, \tag{12}$$

for the initial position of the clock r. The initial position z_0 is arbitrarily defined such that the centre of the Earth coincides with the point of maximum variation of the effective fundamental parameters defined in (3) and (4), so the extremum of their first order derivative. Then considering the hyperbolic profile (5), such a condition arises for $z_0 = \pm 0.658\, d$.

The measured values for the clock biases of each Galileo clocks in comparison with a set of ground references have been retrieved from the Galileo clocks products generated by the European Space Operations Centre (ESOC) during the 3-months campaign from January 1st to April 1st. For each epoch with a time sample Δt of 30s, we calculated $s^a(t)$ as the difference between the clock a bias and the clock E01 bias, so removing the possible disturbances affecting the ground reference stations and the electromagnetic links.

The experimental results for the maximum value of $\Delta s^a(t)$ during the campaign are displayed in Fig. 1 for each selected Galileo satellite. To obtain these results, we first calculated the raw data $\Delta s^a(t)$ epoch by epoch using (8) and considered moving windows of 14 hours in the time series. This 14h duration corresponds to the orbital period of the Galileo constellation. Then, we removed a linear regression in each 14h window. As explained below, the signature of large transients is periodic in the $\Delta s^a(t)$ time series with a period of 14h. So the linear regression technique applied within this time window enables to remove the first and second order drifts in the phase $s^a(t)$ without affecting these possible periodic signatures. In each step, we identified and removed the outliers inherent to the processing of the clock products at the inter-day transition and those related to satellite maneuvers. Finally, we took the maximum clue of each 14h window. It is worthy to note that despite the possible periodic signature, we only consider the maximum clue from one epoch to another. Thus at the level of the zero of the associated possible sine profile of $\Delta s^a(t)$.

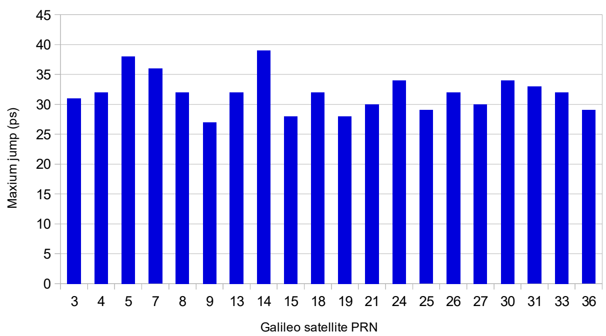

Fig. 1. Experimental value for the maximum frequency jump for each selected Galileo satellite clock in comparison with the reference E01.

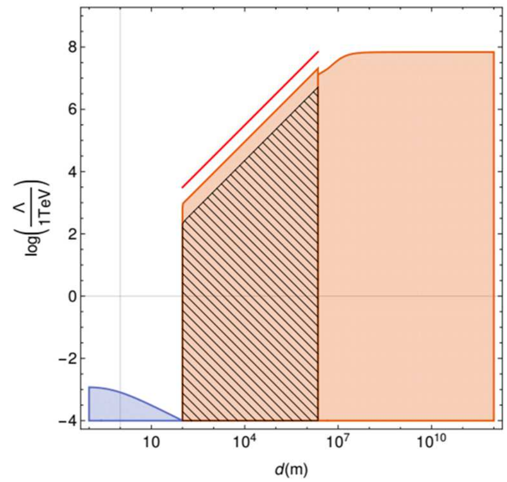

Fig. 2. Graph of constraints on the parameter space with the coupling constant Λ_α versus the size of the transient d, for $\tau = 2$ months. The hatched region represents the constraints previously achieved in [14]. The blue one is the exclusion area after applying the signal propagation method introduced in [16]. Finally, the exclusion area in orange are the Gaston constraints resulting from the single clock maximum jump analysis introduced in this paper. Finally, the red curve is the boundary the possible event detection area after a full correlation analysis.

III. Preliminary Results and Interpretation

Previous analyses with the GPS constellation [6,14] were carried out for the particular case of thin domain walls only, under the rough assumption of a step profile. A DW is considered as thin in our experimental study when the transit time through any clock occurs within the 30-second sampling time Δt, that is:

$$d < v_\perp \, \Delta t \, . \tag{13}$$

We fix the typical relative velocity $v_\perp$ to 300 km/s according to models for the DM galactic halo and the sun motion in the Galactic plane. However, this analysis should be extended to the more realistic velocity profile introduced in [6]. Regarding the improved scalar field profile (5) in the Gaston project with the quadratic interaction (3) or (4), the DW is supposed to be thin when d < 2250 km. The associated exclusion of the parameter space previously obtained in [14] for thin DW only is represented as the hatched region of Fig. 2.

The preliminary results obtained in the Gaston project, see the orange area in Fig. 2, not only improve the existing constraints [14] but also provide a dramatic extension by dealing with any large transient, that is for d > 2250 km. The case of large transients, in which the transit duration covers several sampling times Δt_i, was never considered so far with GNSS atomic clocks. More importantly, the analysis for large values of d applies to all types of transients, not only DW, with the quadratic scalar coupling (3) or (4). However, the general character of the hyperbolic profile as a reasonable approximation is to be checked.

Fig. 1 shows that the maximum frequency jump does not exceed 40 ps for each selected Galileo satellite. This experimental value can be included in (9), leaving 3 undetermined parameters inherent to the transient model: Λ_α (or $\Lambda_{e/p}$), τ and d. Hence, Fig. 2 presents an example of the new exclusion area using our maximum frequency jump method for an encounter time τ of 2 months. The way of interpreting our results is the following: Transient objects with a radial profile similar to (5) and an electromagnetic coupling Λ_α, see (3), inferior to 10^7 TeV (and quasi fulfilling the local DM density) do not exist experimentally if their size d ranges between 10^6 and 10^{12} m and if their mean period of encounter τ is of the order of 2 months. The bound on the associated variation of the fine structure constant $\Delta\alpha/\alpha$ is of the order of 10^{-13}. A similar plot, not presented here, has been obtained for the fermion interaction (4) with the associated coupling constant $\Lambda_{e/p}$.

Unfortunately, the analysis of the signal propagation disturbance described in [16] offers a small exclusion region in the context of this specific model of scalar field interaction and Galileo signals, see the blue area of Fig. 2. It is well below the cosmological constraints of 3TeV brought by supernovae [15]. Indeed, it is important to recall that these models of DM objects are one way among many others to get variations of the fundamental constants observable by our experimental setup. Hence, the constraints on the parameter space for DM models could be extended to other compatible models of variations of fundamental constants. This study is still on-going.

These preliminary results pave the way to a deeper analysis implying the search for candidate events through a time correlation between the whole set of selected Galileo satellites. In parallel to the maximum frequency jump analysis, we simulated also the effect of the transient taking into account for the first time the orbital motion of the satellites. Nevertheless, this trajectory was linearized in order that the frequency difference $\Delta s^a(t)$, see (8), keeps an analytical expression under the first order finite difference between two epochs. The simulation shows a 14 hours periodic signature for the phase $s^a(t)$ or the frequency (8), with an envelope modulation consisting in two lobes covering the whole transit duration: $d/v_\perp$. This periodicity originates from the fact that the gradient of the scalar field in the $\boldsymbol{n}_\perp$-direction induces a phase difference for any Galileo clock a with respect to the reference clock E01. For example, if the gradient is negative, any clock a ahead (in space) of the reference clock in the $\boldsymbol{n}_{\perp}$-direction will be delayed in comparison with the reference clock. After half an orbital period, the same clock a will be back (in space) the reference, so it will get ahead in phase with respect to this reference. And so on during several orbital periods generating a sine signature. The modulation envelop has a zero at the time when the core of the domain wall (or more generally the extremum of the scalar field in the $\boldsymbol{n}_{\perp}$-direction for other types of transients) crosses the center of the Earth, since the gradient of the scalar field change its sign. At that moment, there is a phase shift of 180° in the periodic behaviour of the frequency.

IV. Conclusions and Perspectives

For the already covered value of the size $10^2<d<10^6$ m in [14], the perspectives of possible discoveries are restricted to domain wall-type DM transient structures, recently challenged in [17]. Nevertheless, the stable passive H-masers onboard Galileo satellites already offer a slight improvement of the existing constraints [14]. The improvement of the transient modelisation in comparison with previous studies [14] enables to cover larger regions of the parameter space. Indeed, we address sizes $d > 10^6$ m such that the transit of the DM object covers several sampling times. It is worthy to recall that for $d>10^8$ m, our analysis could apply to transient structures of generalised shape or type provided the quadratic scalar interaction still occurs, see (3) and (4). Our maximum frequency jump method provides a useful strong exclusion area in the parameters space but is not dedicated to a direct detection and is not optimal since it does not consider the time evolution of the datastream nor the correlation between the S/C. Therefore, the next step will be to proceed to the correlation of the data from the different Galileo satellites in order to search for candidate events or to refine our exclusion area. An event is associated to a given pattern of frequency glitches in comparison to a reference that propagate into the Galileo constellation during the transit time. Precise satellite clock measurements will be supplemented by the intensive 3-months SLR measurement campaign on Galileo satellites carried out in the early 2021 to identify and quantify systematics.

For $10^9 < d < 10^{12}$ m, we have demonstrated that transient objects with the quadratic interaction (3) or (4) generate a periodic signature in GNSS clocks comparisons. The associated constraints in the parameter space saturate for large values of d. Actually, the fact that the amplitude of the clock perturbation is proportional to the size d (6) is compensated by the restricted space gradient, obviously limited by the maximum distance between two Galileo satellites. Our frequency jump method offers the first ever constrains with GNSS clocks for so large value of d and τ. However, a possible continuation of the work would be to use Fourier techniques on data series for each satellite in order to search for transient events in this unexplored area of the parameter space. A correlation between different S/C would be a strong indicator of a real event. Considering a campaign of three months as reported in this paper only gives access unequivocally to transient events, when a visible modulation in the amplitude of the periodic signature clearly indicates the start and the end of the event.

Finally, transients of which the size d is larger than 10^{12} m has a transit time larger than the campaign duration. This case will be addressed in a future paper as a straightforward extension of this work and offers an interesting ambiguity. Indeed, for so large sizes, it is impossible to distinguish transient event due to a compact object from large scale variations of the fundamental constants. The raison is simply related to the fact that a periodic signature would be still observable, but the amplitude modulation is no longer detectable. In other words, our study is easily generalisable to a test of fundamental constants on large spatial scales, namely $d > 10^{12}$ m for a 3-months campaign, in the limit of the model of a hyperbolic tangent profile for the scalar field. This novel perspective will be addressed in a future paper. Notice that within the transient object interpretation, the value of τ should be statistically determined in order to avoid the superposition of transients.

The present research shows for the first time that it possible to look for large scale transient variation or large-scale permanent variations of fundamental constants using the orbital properties of GNSS satellites. The interesting property that is presently used is the periodic motion of atomic clocks in comparison to a reference. Other periodic motions of atomic clock could be considered. For example, annual modulations of clocks difference, due to the orbital motion of the Earth around the sun could be investigated between ground-based active H-Maser (AHM) freely running and AHM steered by an external Caesium fountain or optical clock.

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