The Superior Conjunction Experiment of BepiColombo

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Abstract

Launched in October 2018, the ESA/JAXA BepiColombo mission is currently in cruise to reach Mercury in late 2025. The Mercury Orbiter Radioscience Experiment (MORE) is one of the 16 instruments hosted on board the spacecraft. Testing general relativity is among the primary objectives of MORE. Superior conjunction experiments (SCE) will be performed during the interplanetary trajectory, with the aim of obtaining an accurate estimate of the post-Newtonian parameter γ. This is allowed by MORE advanced radio tracking system which provides precise range and Doppler data almost at all solar elongation angles, thus enabling an accurate measure of the relativistic time delay and frequency shift undergone by the signal when the spacecraft is in a superior solar conjunction (SSC). The rst BepiColombo SCE will take place in March 2021, and others will follow during the cruise phase. The nal objective is to place new limits to the accuracy of the general relativity as a theory of gravity in the weak eld limit, improving previous result from the Cassini SCE (Bertotti et al. 2003), which was able to determine that γ-1=(2.1$\pm$2.3)$\times$10-5. Because of the proximity to the Sun, the spacecraft will undergo severe solar radiation pressure acceleration, and the effect of the random uctuations of the solar irradiance may become a major concern. We address the problem of a realistic estimate of the outcome of the SCE of BepiColombo, by including the effects of solar irradiance random variations in the dynamical model. We analyzed the experiment under different assumptions on the ranging system performances, observation coverage and solar activity showing their impact on the attainable result. We propose a numerical method to mitigate the impact of the variable solar radiation pressure on the scienti c result. Our simulations show that, exploiting data from multiple SSCs, the accuracy obtainable in the relativistic time delay measurement is 13$\times$10-6 for a strong solar activity, and 6$\times$10-6 for weak irradiance uctuations. We found that the latter result can be obtained by the rst SSC alone if the plasma noise calibration works until the impact parameter reaches 6 solar radii.

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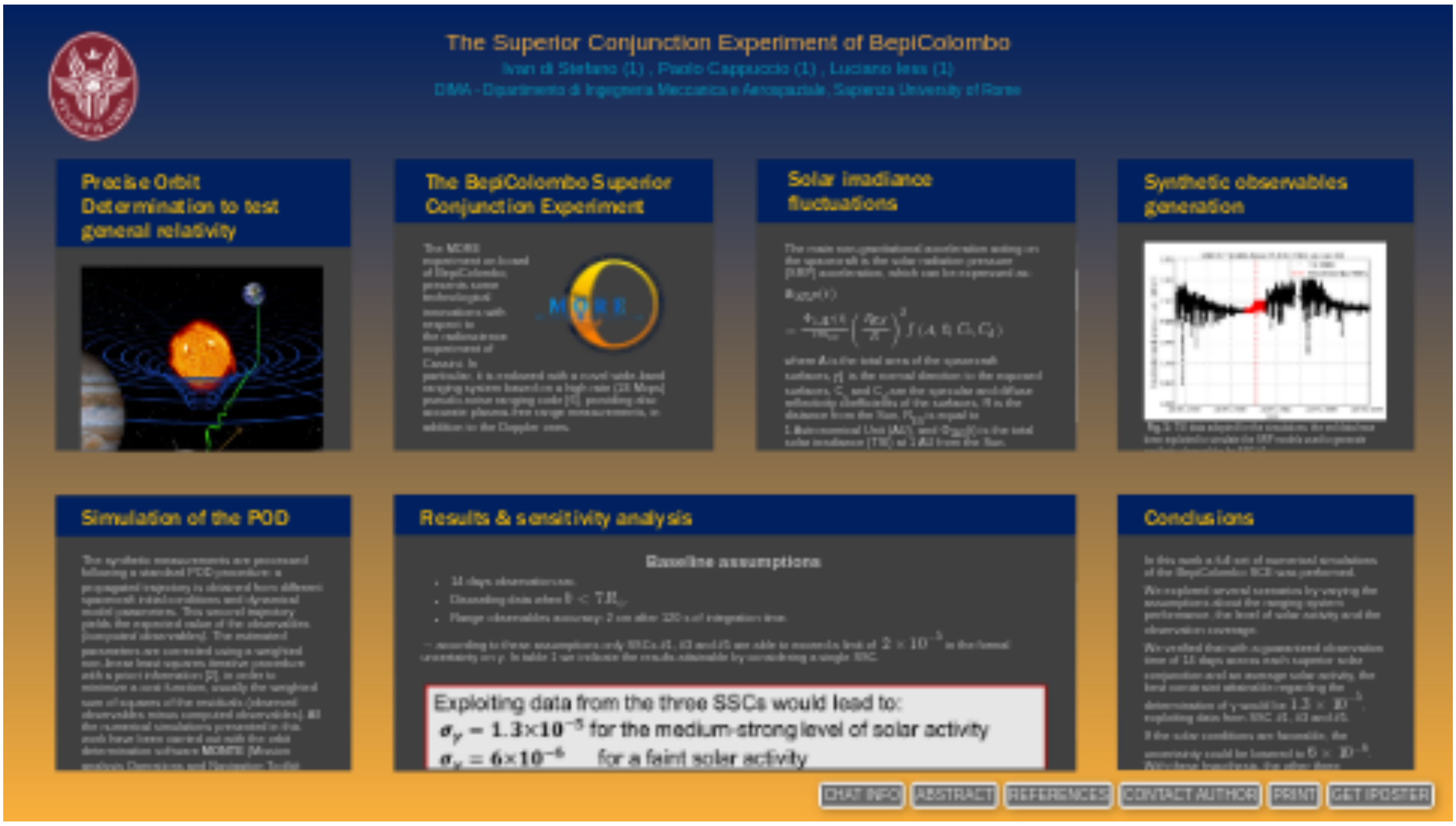

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PRECISE ORBIT DETERMINATION TO TEST GENERAL RELATIVITY

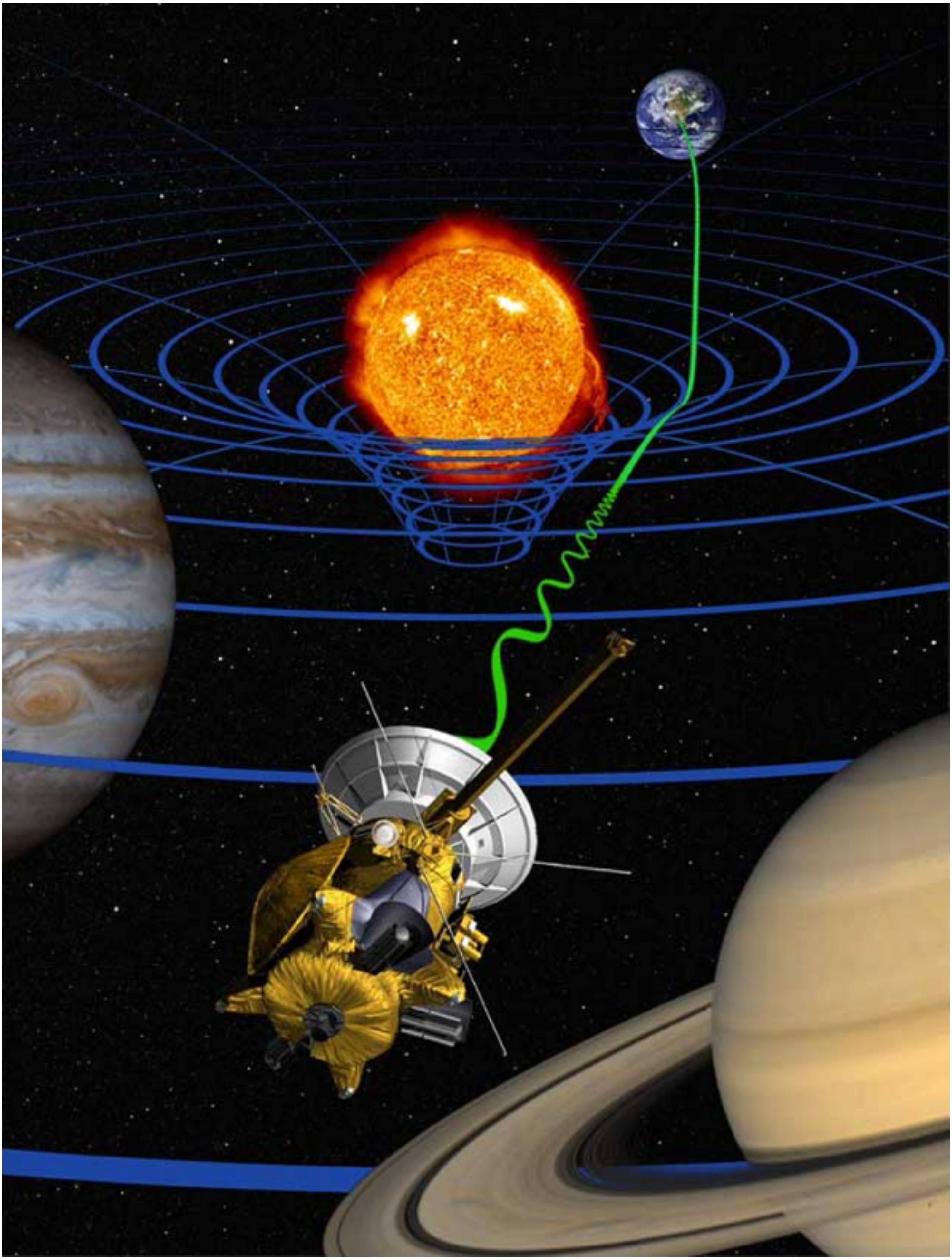


Fig. 1: Cassini superior conjunction experiment representation ([4])

During the cruise phase of ESA's BepiColombo mission to Mercury, the Mercury Orbiter Radioscience Experiment (MORE) [1] will probe general relativity through a Superior Conjunction Experiment (SCE).

MORE will exploit a Precise Orbit Determination (POD) [2] process to measure the Shapiro time delay and the consequent frequency shift aiming at the determination of the **post-Newtonian parameter γ**, which roughly controls the amount of space curvature produced by the mass of the Sun. The space components of the metric tensor depend on γ (which is equal to 1 in general relativity). Any detected deviation from the unit value would represent a **violation of the general relativity theory.**

The SCE is based on the exchange of a radio-signal between the spacecraft and an Earth station during a superior solar conjunction (SSC, Fig. 2). While passing near the Sun, the signal undergoes a relativistic time delay and frequency shift, which are detectable through the range and range-rate observables collected for POD experiments.

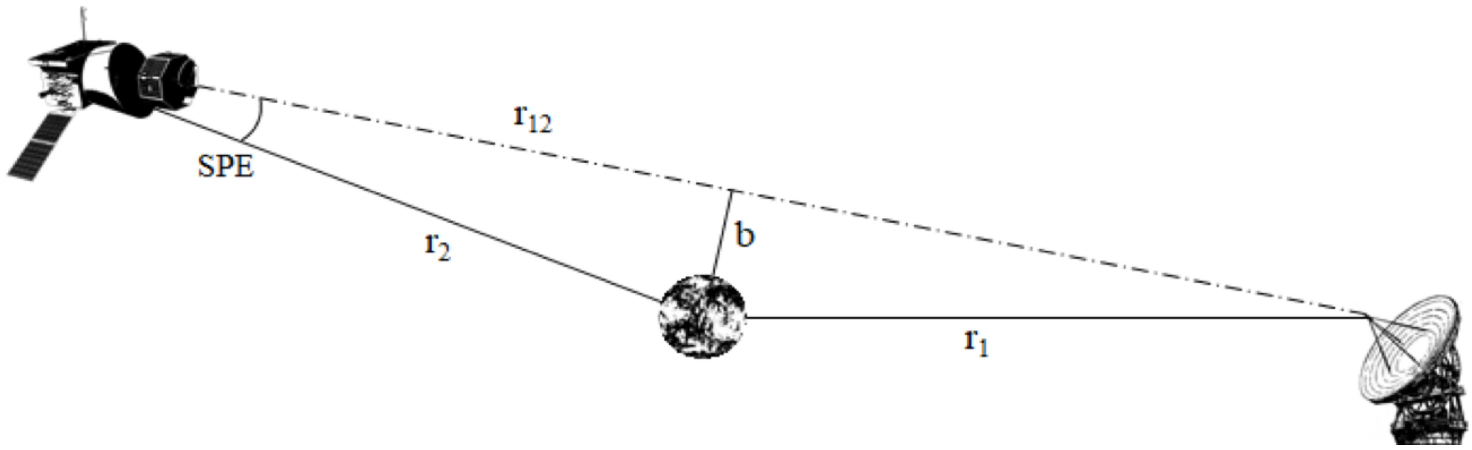


Fig.2: The geometrical configuration of a superior solar conjunction.

In the case of small impact parameters b (see Fig.2) it is possible to express these quantities as a function of γ according to the following approximation [3]:

Shapiro time delay:

$$\Delta t = \frac{(1+\gamma)GM_{\odot}}{c^3} ln\left(\frac{r_1 r_2}{b^2}\right) \approx 60\,\mu s \quad (18\,km)$$

Frequency shift:

$$\frac{\Delta\nu}{\nu} = -\frac{2(1+\gamma)GM_{\odot}}{c^3 b}\frac{db}{dt} \approx 10^{-10} \quad \left(3\,\frac{cm}{s}\right)$$

Thus, the phenomenon is enhanced in the case of decreasing b and increasing db/dt.

The best constraint on γ available so far is the one provided in 2002 by the SCE of NASA's **Cassini mission** [4], which determined that:

$$(\gamma - 1) = (2.1 \pm 2.3) \times 10^{-5}$$

This was possible thanks to plasma-free Doppler observables retrieved during a SSC: the dispersive plasma noise due to the solar corona (which is intensified in SSCs) has been completely canceled out through a compensation scheme based on a multi-frequency link [5] in **X/X** (7.2 GHz uplink/8.4 GHz downlink), **X/Ka** (7.2/32.5 GHz) and **Ka/Ka** (34/32.5 GHz) bands.

THE BEPICOLOMBO SUPERIOR CONJUNCTION EXPERIMENT

The MORE experiment on board of BepiColombo, presents some technological innovations with respect to the radioscience experiment of Cassini. In particular, it is endowed with a novel wide-band ranging system based on a high rate (24 Mcps) pseudo-noise ranging code [6], providing also accurate plasma-free range measurements, in addition to the Doppler ones.

During its 7-year cruise phase (2018-2025) BepiColombo will experience 11 SSCs, and according to project's indications, six of them will be free from thrusted arcs (see Fig.3) and thus available for the general relativity test (when the solar electric propulsion system is active, the measurements would be useless due to the large dynamical noise).

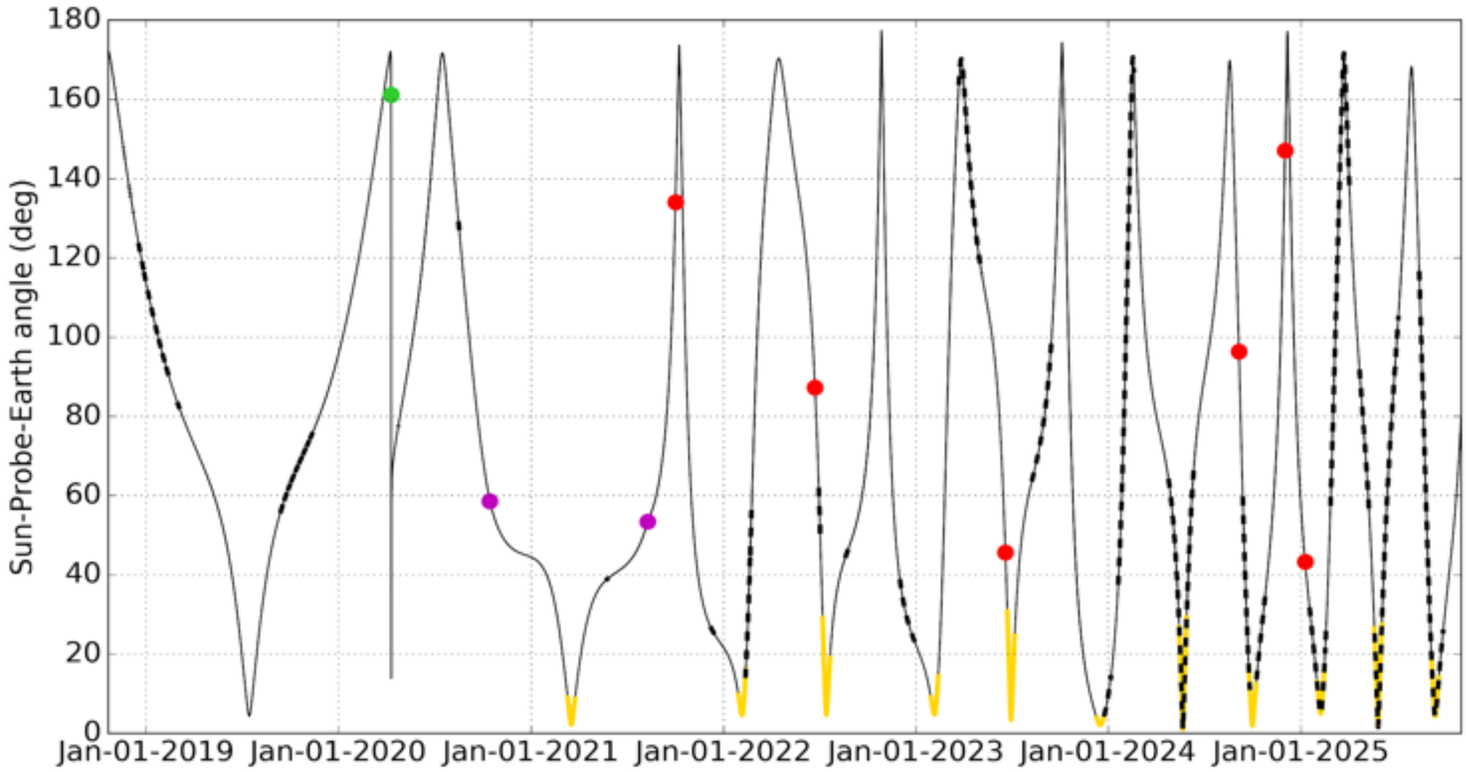


Fig.3: The Sun-Probe-Earth angle evolution (black line) during BepiColombo interplanetary trajectory. Superior solar conjunctions occur when SPE is close to zero. Yellow line evidences a period of 14 days across the SSCs; the black dashed line indicates thrusted arcs; green, purple and red dots represent Earth, Venus and Mercury flybys, respectively.

If the dynamical model of the spacecraft was perfectly known, the precise tracking system of MORE would be able to improve the result of Cassini SCE by **one order of magnitude** [7]**.**

However, not all the forces acting on the spacecraft will be known or modeled with the precision needed for this result [8].

SOLAR IRRADIANCE FLUCTUATIONS

The main non-gravitational acceleration acting on the spacecraft is the solar radiation pressure (SRP) acceleration, which can be expressed as:

$$\mathbf{a}_{SRP}(t) = \frac{\Phi_{1AU}(t)}{c\, m_{sc}} \left(\frac{R_{ES}}{R}\right)^2 f\left(A, \hat{n}, C_s, C_d\right)$$

where A is the total area of the spacecraft surfaces, $\hat{n}$ is the normal direction to the exposed surfaces, C_s and C_d are the specular and diffuse reflectivity coefficients of the surfaces, R is the distance from the Sun, R_{ES} is equal to 1 Astronomical Unit (AU), and $\Phi_{1AU}(t)$ is the total solar irradiance (TSI) at 1 AU from the Sun.

$\Phi_{1AU}(t)$ presents random temporal fluctuations at the level of 0.01-0.1% in few days.

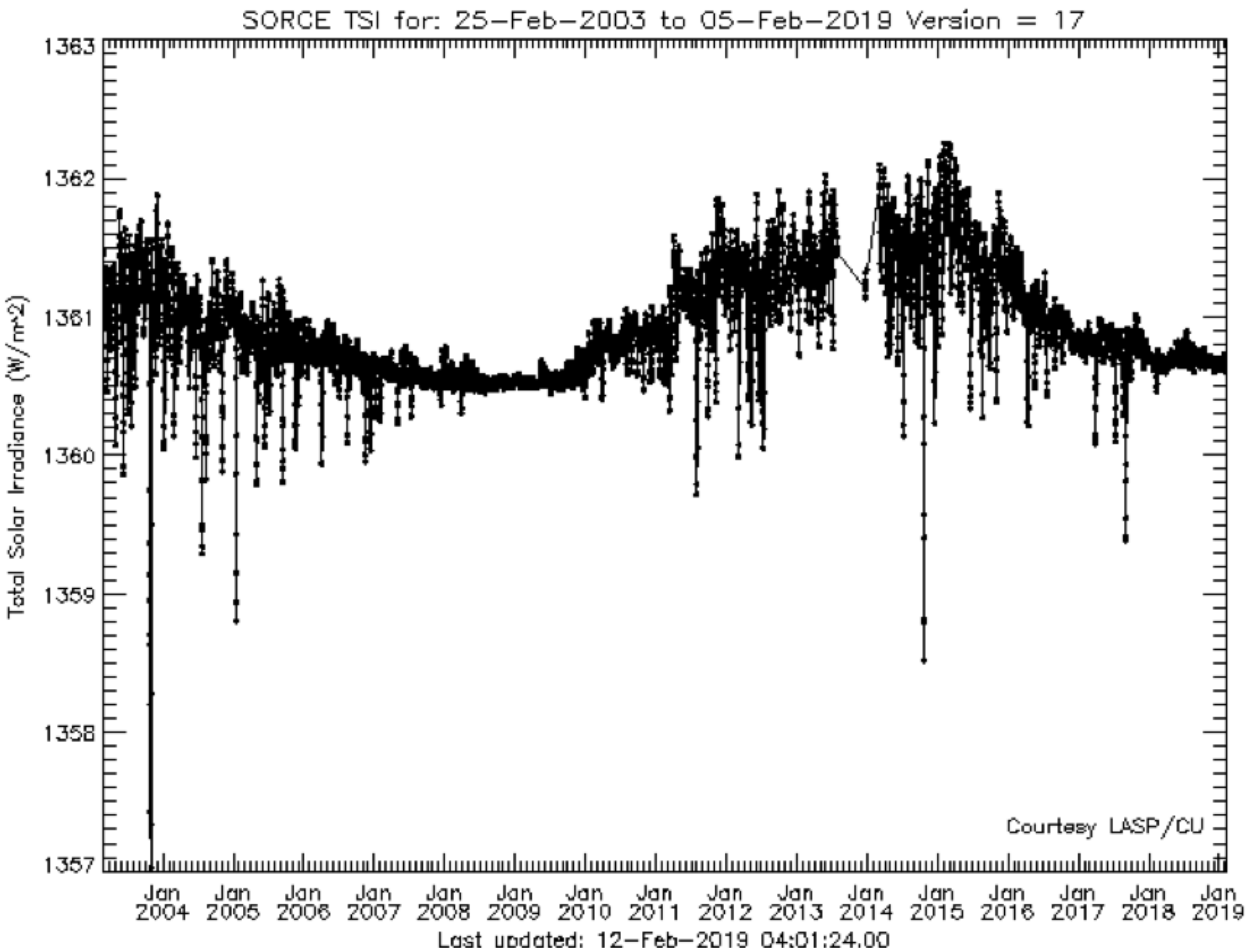


Fig. 4: Total solar irradiance measured by NASA's SORCE mission in the last 11 years.

Solar emission is anisotropic thus we cannot take advantage of radiometers' measurements of $\Phi_{1AU}(t)$ to infer the solar radiation pressure acting on the spacecraft during a SSC.

This means that the SRP acceleration during the SCE will be predictable only to 0.1-0.01%.

We verified that this residual unknown acceleration causes an effect on the observables which is of the same order of magnitude of the relativistic signal to be detected.

The maximum dynamical effect due to δa_{srp} in 1 day is about:

$$\delta v \approx \delta a_{srp} \times \tau \approx 10^{-6} - 10^{-5} m/s$$

$$\delta s \approx \delta a_{srp} \times \tau^2 \approx 0.1 - 1m$$

For this reason, we performed the simulations of the SCE of BepiColombo including solar irradiance fluctuations in the dynamical setup adopted for the generation of the synthetic range and range-rate observables. Our aim is to analyze the effect on the result of the experiment, obtaining a reliable prediction on the attainable accuracy on the estimate of γ.

SYNTHETIC OBSERVABLES GENERATION

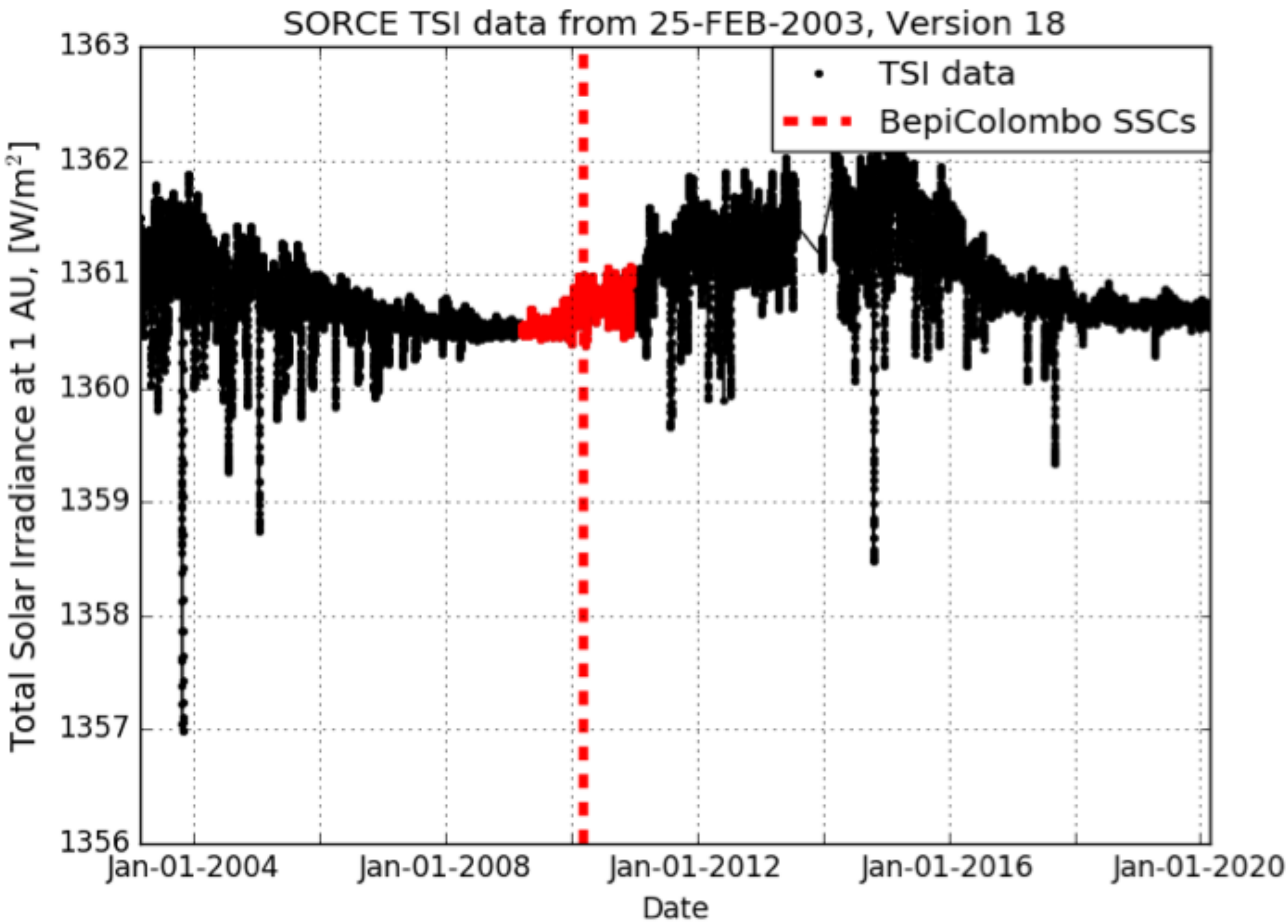


Fig. 5: TSI data adopted for the simulations: the red data have been exploited to simulate the SRP models used to generate synthetic observables for SSC #1.

The numerical simulations of the SCE are based on the generation of synthetic range and range-rate data (observed observables). To retrieve the simulated observed observables, we build a realistic setup and then propagate a simulated trajectory (reference trajectory), starting from initial conditions of the spacecraft obtained from the SPICE kernels [9] of the BepiColombo mission. The dynamical model used to obtain the reference trajectory is based on a number of adjustable parameters. Using an observation model, we then generate the observed observables from this trajectory. The observed observables contain also noise whose statistical properties are those expected for the MORE radiometric data [10].

Simulation setup - main features

- Observed observables were generated including solar irradiance fluctuations in the dynamical model, changing the input SRP pattern among 50 SRP models (retrieved by irradiance measurements of NASA's SORCE mission) corresponding to appropriate solar activity for each SSC.
- We discarded all the data retrieved when $b < 7R_\odot$(if the signal is too close to the solar corona, the plasma-noise cancellation scheme fails [10]).
- Solar arrays attitude has been set as variable with the distance from the Sun (see [12]) to avoid degradation or a failure of the solar cells.
- Indications from the BepiColombo project (November 2019) fixed the minimum duration for the observation arc to 14 days across the SSC (with possible extensions). Only six of the eleven SSCs available during the cruise are exploitable for the SCE (see Fig. 3).
- MORE radiometric observables accuracies:

  3 µm/s in range rate @ 1000 s;

  2 cm range @ 120 s [10];

SIMULATION OF THE POD

The synthetic measurements are processed following a standard POD procedure: a propagated trajectory is obtained from different spacecraft initial conditions and dynamical model parameters. This second trajectory yields the expected value of the observables *(computed observables)*. The estimated parameters are corrected using a weighted non-linear least squares iterative procedure with a priori information [2], in order to minimize a cost function, usually the weighted sum of squares of the residuals (observed observables minus computed observables). All the numerical simulations presented in this work have been carried out with the orbit determination software **MONTE** (Mission analysis Operations and Navigation Toolkit Environment), developed by NASA JPL [13].

The dynamical model used to perform the POD simulation is the same as the one used to generate the observed observables, **except for the SRP model.**

To represent the lack of knowledge of the TSI fluctuations, the SRP is modeled with a **constant irradiance value at 1 AU from the Sun.**

We included in the list of estimated parameters:

- The state vector of the spacecraft
- The Eddington parameter γ (the a priori uncertainty is based on the result of Cassini)
- One range bias in each observation arc (with an a priori uncertainty of 6 m)
- A constant scale factor for solar irradiance to adjust its central value.
- A **time-variable stochastic scale factor** multiplying the solar flux reference value to model the SRP fluctuations and absorb their adverse effect.

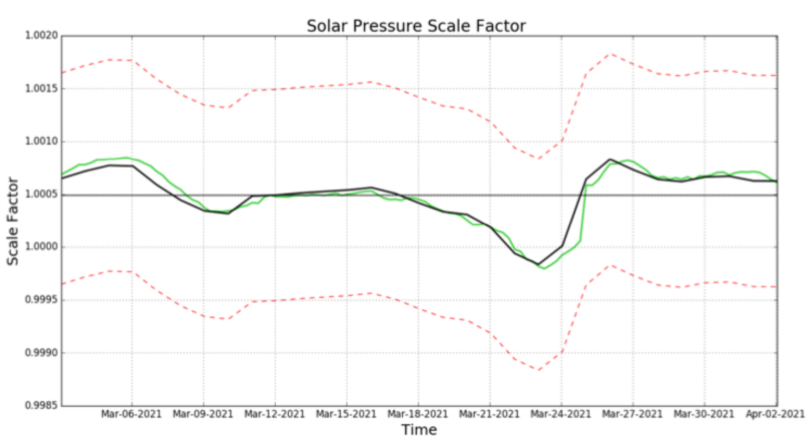
The scale factor is a random process, which assumes different values in batch times inside the observation arc.

To represent the behavior of solar irradiance fluctuations, we describe the scale factor as an exponentially correlated random variable, which time evolution is ruled by the *Langevin differential equation*:

$$\dot{\eta} = -\frac{1}{\tau}\eta(t) + u(t)$$

therefore, the time evolution of the stochastic process η depends on a white noise contribution u(t) and a deterministic term controlled by a time constant τ.

The results of the simulations show that the SRP oscillations are satisfactorily reconstructed (see Fig. 6), but at the cost of an unavoidable increase on the estimation uncertainty on γ (see Results & sensitivity analysis)



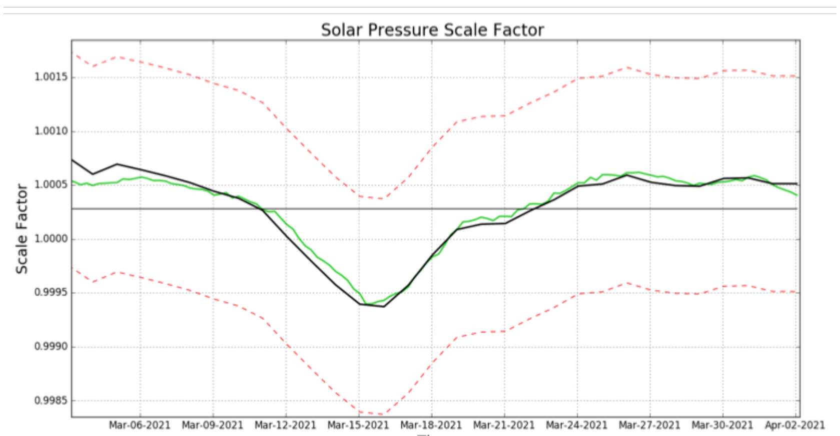


Fig.6: Estimation of solar irradiance fluctuations: the green line represents the simulated SRP model while the black line is the one reconstructed with a batch time of 24 h and a conservatively large a priori uncertainty of 1×10^{-3}. The red dashed lines represent the three-sigma interval.

RESULTS & SENSITIVITY ANALYSIS

Baseline assumptions

- 14 days observation arc.
- Discarding data when $b < 7R_{\odot}$.
- Range observables accuracy: 2 cm after 120 s of integration time.

→ according to these assumptions only SSCs #1, #3 and #5 are able to exceed a limit of 2×10^{-5} in the formal uncertainty on γ. In table 1 we indicate the results attainable by considering a single SSC.

Exploiting data from the three SSCs would lead to:
$\boldsymbol{\sigma_\gamma = 1.3{\times}10^{-5}}$ for the medium-strong level of solar activity
$\boldsymbol{\sigma_\gamma = 6{\times}10^{-6}}$ for a faint solar activity

	Average result ($\times 10^{-5}$)	Best case ($\times 10^{-5}$)
SSC #1	1.9	0.73
SSC #3	1.9	0.71
SSC #5	1.8	1.14

Table 1: Uncertainty on the estimation of γ considering baseline assumptions. The first column describes the average of the results obtained through the 50 simulations performed with the different SRP models, while in the second column the best cases are reported.

Sensitivity analysis

- The applicability of the plasma noise cancellation procedure depends on the value of the impact parameter. The quality of the data deteriorates gradually when the signal path digs deep into the solar corona. We assume a perfect plasma noise removal till the selected value $b = 7R_{\odot}$ and we discard data collected below this threshold. At the same time, the outcome of the test can be improved with lower threshold value of the impact parameter. As a precise prediction to understand which is the limit of operation of the plasma compensation scheme is not available, it is worthwhile to explore the outcome of the experiment when the multi-frequency plasma compensation scheme is effective at smaller impact parameter cut-off values. Fig. 7 shows the formal uncertainty on the estimate of γ attainable in each SSC as a function of the threshold impact parameter.

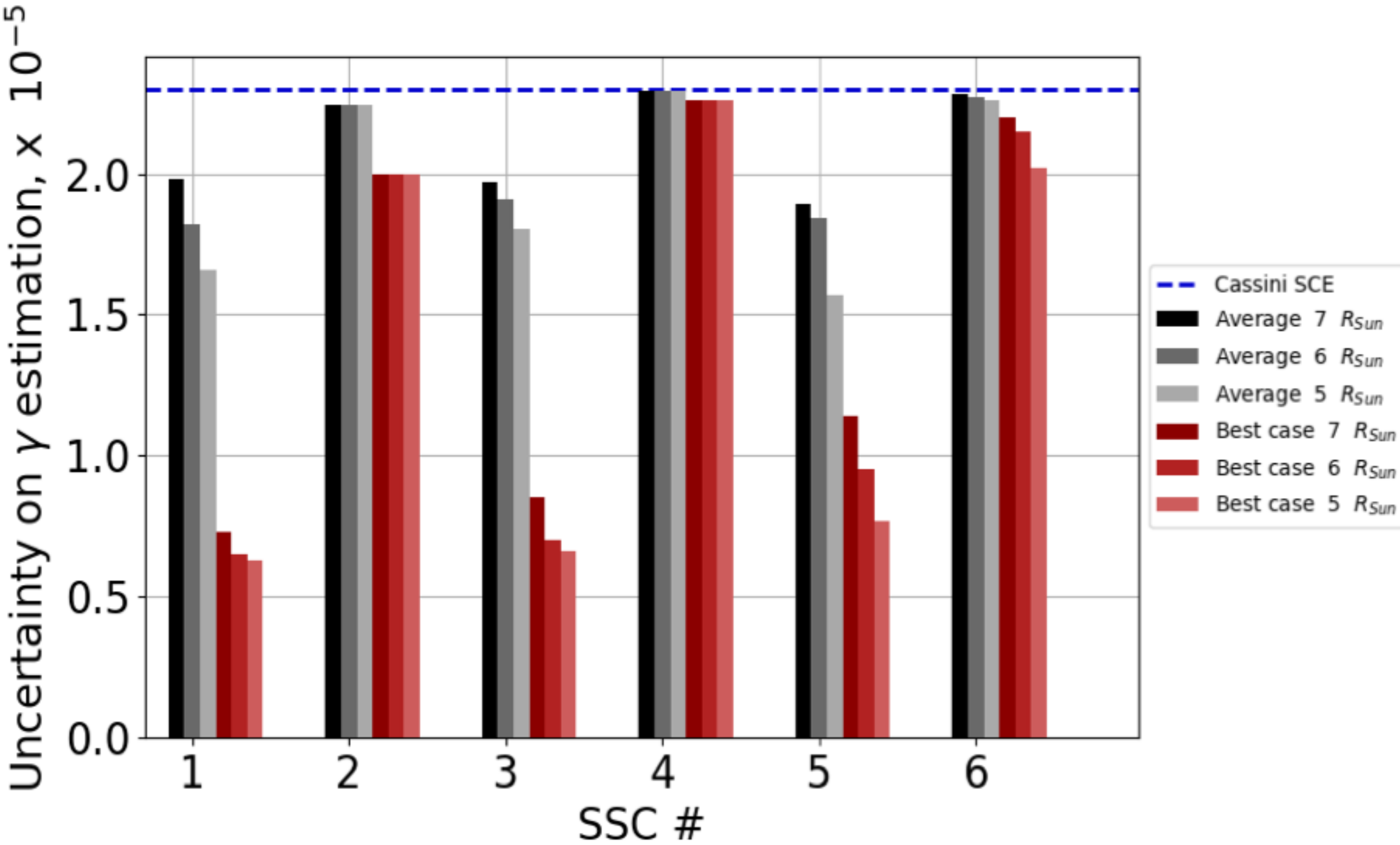


Fig. 7: Uncertainty on γ for different threshold values of the plasma noise calibrations.

- An extension of the observation arc duration allows, in general, to better constrain the trajectory across the solar conjunction and to tighten the uncertainties in all estimated parameters. However, when taking into account the random unmodeled non-gravitational perturbation caused by the TSI fluctuations, an improvement of the experiment result as a consequence of a wider observation window is not assured: in case of medium to large SRP fluctuations, even extending the observation arc duration to 30 days, the outcome of the SCE would not be considerably improved. On one hand, a larger observation window would provide for additional data to detect the relativistic signal, on the other hand, the unknown SRP variations are acting for a longer time, accumulating the effect on the observables. In the case of a weak solar activity, a variable observation window duration would lead to different results (Fig. 8). It is worth noticing that some SSCs show a larger formal uncertainty on γ rather than the expected improved estimation. This behavior is due to the fact that an irradiance oscillation pattern free from intense fluctuations for a longer time is uncommon. However, if the observation window is entirely free from any severe TSI oscillation, the accuracy attainable on γ could be considerably better with a longer dataset. With an extension to 20 days, SSCs #2 and #4 become more valuable opportunities. Therefore, an extension of the observation window, when possible, would be an important factor to increase the probability of a better determination of γ.

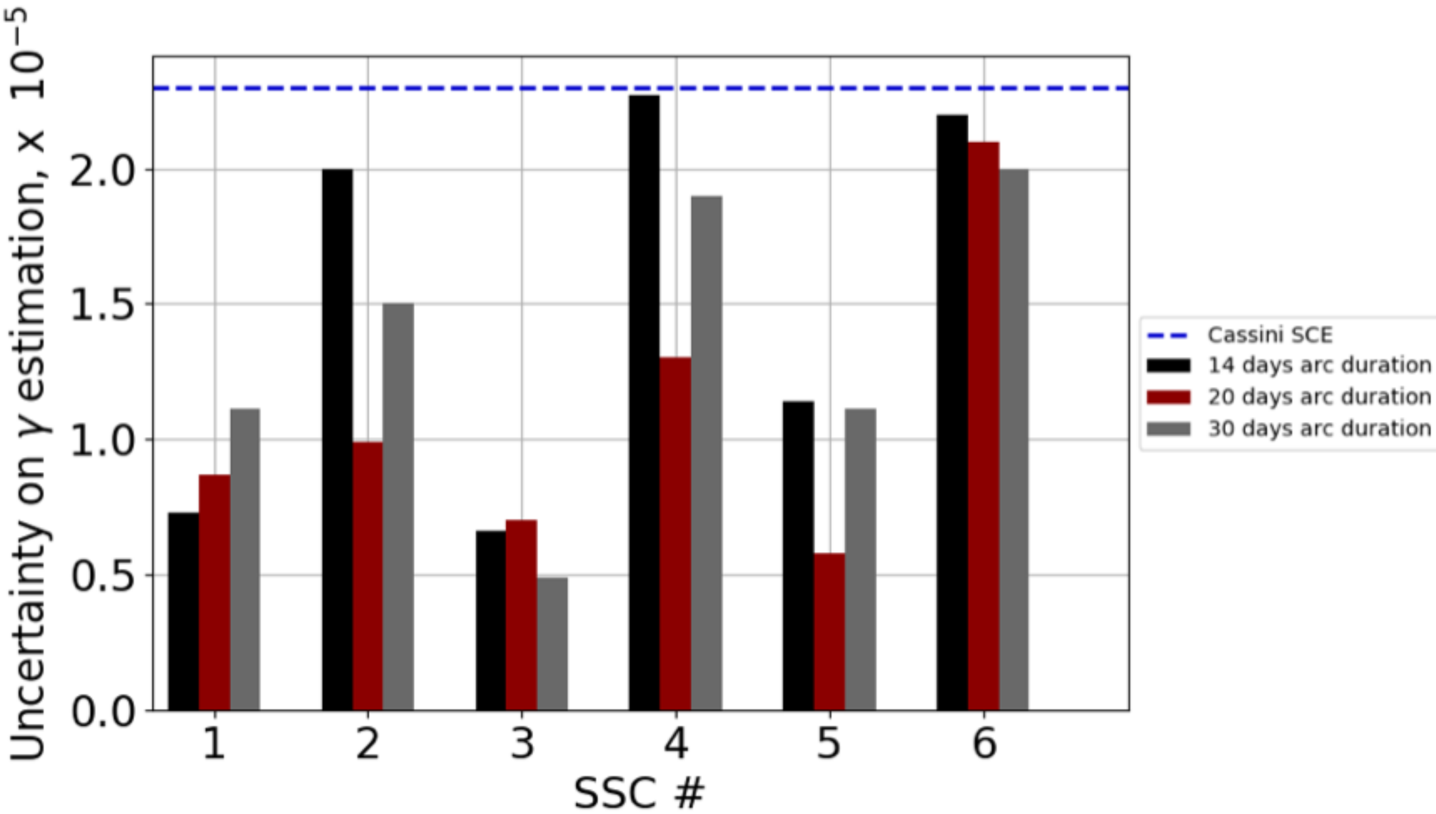


Fig. 8: Variation of the formal uncertainty on γ with an extension of the observation window

- We also verified that, because of the presence of strong irradiance fluctuations, having a larger noise on range measurements (20 cm with 300 s of integration time) would not lead to a significant deterioration of the result. Considering a faint solar activity, the effect of the degraded accuracy in range is more noticeable: for SSCs #1, #3 and #5 the formal uncertainty on γ increases respectively by 168%, 64%, and 3.5 %.

CONCLUSIONS

In this work a full set of numerical simulations of the BepiColombo SCE was performed.

We explored several scenarios by varying the assumptions about the ranging system performance, the level of solar activity and the observation coverage.

We verified that with a guaranteed observation time of 14 days across each superior solar conjunction and an average solar activity, the best constraint attainable regarding the determination of γ would be 1.3×10^{-5}, exploiting data from SSC #1, #3 and #5.

If the solar conditions are favorable, the uncertainty could be lowered to 6×10^{-6}. With these hypothesis, the other three exploitable conjunctions (SSC #2, #4, #6) would not contribute significantly to the determination of γ.

However, we have found that an extension of the observation window to 20 days would bring significant gains to SSC #2 and SSC #4 (Fig. 8).

We also assessed the effect of the availability of good plasma calibrations at smaller impact parameters for each one of the three best SSCs. It should be remarked that SSC #1 happens during a solar minimum, therefore it is plausible to consider a weak solar activity, and a full operation of the plasma noise cancellation scheme until 6 solar radii: in this case, thanks to the conjunction of March 2021 alone, γ would be determined with an accuracy of 6×10^{-6}.

However, if suitable models to predict TSI fluctuations on the hidden face of the Sun will be available (e.g. via correlations with measured acoustic modes on the visible side), the outcome of the experiment can be substantially improved: the more accurately these predictive models can describe the irradiance fluctuations, the closer the results will come to an improvement of one order of magnitude of the Cassini result.

Acknowledgments

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ABSTRACT

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