Fast Orbit Feedback and Beam Stability at the Swiss Light Source

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Abstract. A global, fast orbit feedback (FOFB) based on the digital beam position monitor (DBPM) system has been in user operation at the Swiss Light Source (SLS) since November 2003. The SVD-based correction scheme acts at a sampling rate of 4 kHz using position information from all 72 DBPM stations and applying corrections with all 72 horizontal and 72 vertical corrector magnets. As a result, the FOFB damps successfully orbit distortions, which are mainly caused by ground and girder vibrations as well as the 3-Hz booster crosstalk. It also allows fast and independent ID gap changes, which are completely transparent to all SLS users. With top-up as a regular operation mode at SLS, global beam stability on a μm-level has been achieved from days to milliseconds.

INTRODUCTION

The Swiss Light Source (SLS) is a third generation synchrotron radiation facility, which is in operation since the mid of 2001. Successful user operation requires the reproduction and stabilization of a previously established reference orbit ("golden orbit") well below the resolving power of the experimental stations. Photon energy resolution of crystal monochromators in the order of 10^{-4} to 10^{-5} translate into requirements for angular electron beam stability of < 1 μrad corresponding to photon beam motion of < 10 μm at the first optical elements of the beamlines. Photon beam intensity modulations of < 1% on the samples require stabilization of the electron beam position within $1/10^{th}$ of its size at the radiation source points. For the low β insertion device (ID) straights of the SLS, this corresponds to tolerable vertical electron beam motions of < 1 μm.

During the first two years of SLS operation, the above mentioned stability requirements were achieved by a central high level application, the so called slow orbit feedback (SOFB), which automatically performed global orbit corrections at an update rate of ≈ 0.5 Hz [1]. However, the growing number of beamlines performing fast and independent ID gap-scans as well as the increasing sensitivity of the experiments to orbit distortions caused by ground vibrations and environmental noise, required an increase of orbit correction bandwidth. This has been realized by commissioning the SLS fast orbit feedback (FOFB) during the year 2003, which was designed to correct orbit perturbations in a frequency range of up to 100 Hz to a μm level.

FOFB ARCHITECTURE

As a result of the localized structure of the SVD-inverted corrector / BPM response matrix, where only the diagonal and their adjacent coefficients have non-zero values [2], the global SLS FOFB has been realized in a de-centralized architecture. The FOFB is therefore an integral part of the SLS digital BPM (DBPM) system [3], which is distributed over the 12 sectors of the SLS storage ring. Each DBPM consists of a RF front end and a quad digital receiver. The horizontal and vertical position readings of all six BPMs per sector are processed on a single DSP board. For orbit display in the control room and in case of centralized orbit manipulation via a high level SW application (like the SOFB), all 12 DSP boards are connected to the control system via the VME-bus. In case of the FOFB, the feedback algorithms are performed in parallel on the 12 (local) DSP boards and data are directly exchanged between adjacent sectors via fast fiber optic links. This structure allows the calculation of the required corrector magnet kicks per sector based on 18 beam position readings (three adjacent sectors) at a rate of 4 kHz. The resulting corrector kicks are fed into one PID controller per corrector. The FOFB is initialized and monitored by a central PC-based beam dynamics server, which takes the number of available BPMs and correctors into account. Any off-energy trajectories in the horizontal plane are corrected by the central RF frequency. Since the resulting frequency corrections are carried out by a slow high level application on the central beam dynamics server, dispersion orbits must not be corrected by the FOFB and have to be subtracted before each orbit correction.

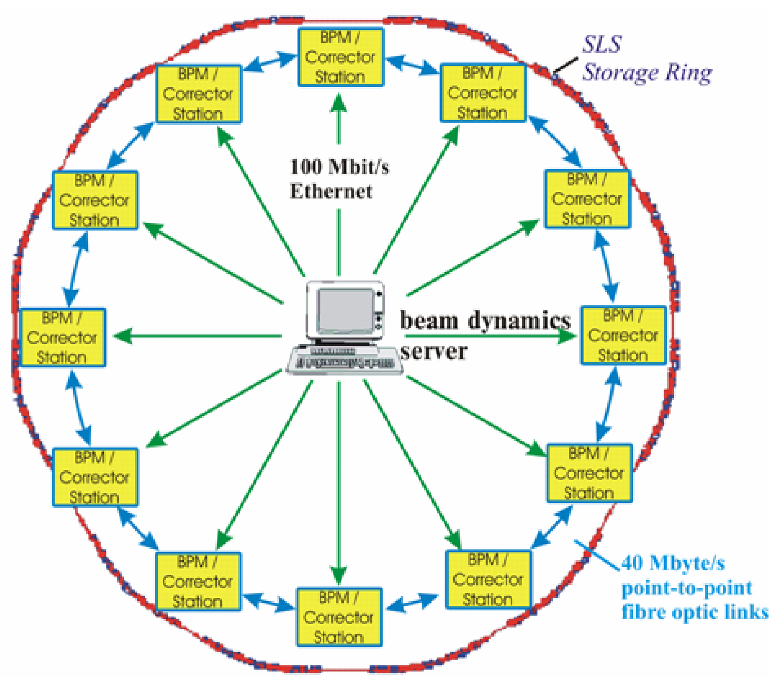

FIGURE 1. De-centralized architecture of the SLS fast orbit feedback. The FOFB is an integral part of the SLS DBPM system and therefore integrated in the twelve BPM / corrector stations (sectors) of the SLS storage ring. A dedicated fiber optic network provides communication between adjacent sectors. The FOFB is initialized and monitored by a central beam dynamics server.

FOFB OPERATIONAL EXPERIENCE AND PERFORMANCE

The FOFB has been operational during SLS user shifts since November 2003. The overall reliability of hardware and software has been the main focus during the first phase of operation. Therefore, the FOFB has been operated at moderate PID loop gains and DBPM filter settings providing a regulation bandwidth of about 60 Hz. In order to avoid beam loss due to malfunctioning FOFB components, a low level security package has been implemented monitoring FOFB parameters and sub-systems performance. When exceeding pre-defined deadbands, the FOFB is automatically stopped and a corresponding alarm is displayed to the operator, who can thus decide on calling in an expert or continuing with FOFB operation. Operational experience of the FOFB shows up to now an overall availability of > 95%. Although most of the automatic interruptions of FOFB have been caused by malfunctioning of DBPM electronics and corrector magnet power supplies, a growing number of FOFB interruptions are caused by users, which are performing beamline commissioning during regular user shifts.

The actual bandwidth of the FOFB as it is presently operated at SLS is 100 Hz in both transverse planes. Although the overall loop delay, which has been measured to be in the order of 1.6 ms, could not be reduced by a DBPM firmware upgrade, the synchronization of all DBPM electronics allowed the use of a more stringent set of PID parameters, which finally leads to the operation of the FOFB close to its design parameters [2]. Fig. 2 shows the measured FOFB closed loop transfer function for both transverse planes. Orbit perturbations up to 100 Hz are effectively damped, while noise sources between 100 – 300 Hz are moderately excited.

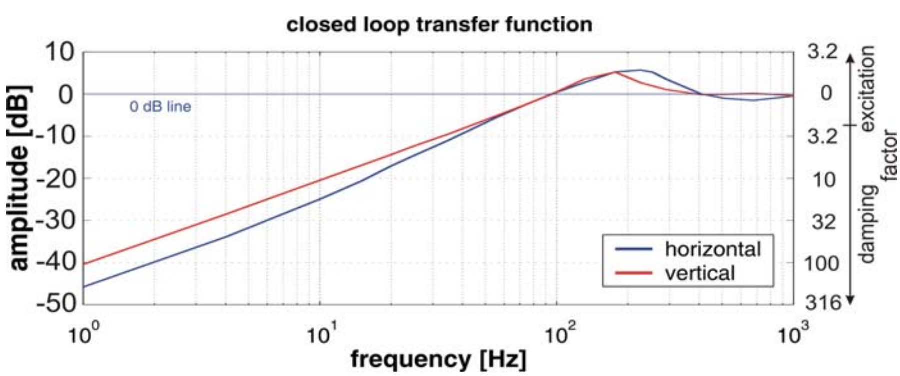

FIGURE 2. Measurement of FOFB closed loop transfer functions in both transverse planes. Effective damping of orbit perturbations has been achieved close to the FOFB design goal of 100 Hz.

Similar to other light sources, the main orbit perturbations at SLS in the frequency range up to 100 Hz are dominated by the following features:

- booster respectively injector operation (3 Hz),
- vibrations at the girder eigenmodes (15 – 30 Hz)
- 50 Hz induced by power supply noise and / or asynchronous pumps.

Snapshots of the horizontal and vertical power spectral densities and integrated spectral densities (see inlets) with and without FOFB measured at the tune BPM outside the feedback loop are shown in fig. 3. It can clearly be seen, that orbit perturbations caused by booster operation, which is in the same tunnel as the storage ring and which is continuously running during “top-up” operation of the SLS, as well as girder vibrations are significantly damped. The 50 Hz peaks are still reduced by a factor of 3 - 5, while noise contributions above 100 Hz are moderately increased.

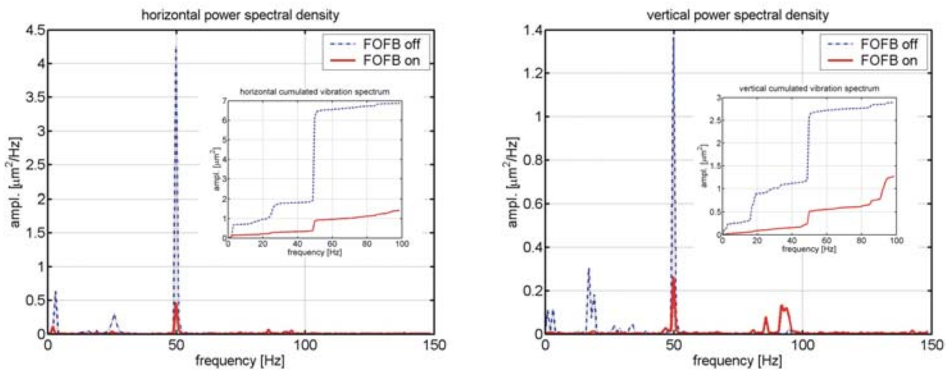

FIGURE 3. Snapshots of the horizontal and vertical power spectral densities and integrated spectral densities (inlets) measured at the tune BPM outside the FOFB loop, with FOFB off and on. Orbit perturbations within the FOFB bandwidth (100 Hz) are significantly damped.

Table 1 summarizes the improvements of beam stability at SLS with the FOFB running compared to the situation without feedback. The values still contain the noise contribution of the DBPM system, which has been measured to be < 0.13 μm within the FOFB bandwidth. Orbit distortions caused by ID gap changes, which would emphasis the effectiveness of the FOFB even more are not included. The temporal RMS values are integrated over the active range of the FOFB (up to 100 Hz) and up to 150 Hz, where significant noise contributions could still be observed. The temporal RMS values at a location s in the storage ring are obtained from the table by multiplication with $\sqrt{\beta(s)}$. At the location of the tune BPM with $\beta_y = 18$ m (see fig. 3) this translates into vertical temporal RMS values of $\sigma_y = 1.15$ μm, while at the source points of the SLS low gap insertion devices ($\beta_y = 0.9$ m) the integrated vertical beam motion up to 100 Hz yields to $\sigma_y = 0.25$ μm.

	horizontal		vertical	
FOFB	off	on	off	on
1- 100 Hz	**0.83 μm · $\sqrt{\beta_x}$**	**0.38 μm · $\sqrt{\beta_x}$**	**0.40 μm · $\sqrt{\beta_y}$**	**0.27 μm · $\sqrt{\beta_y}$**
100-150 Hz	0.08 μm · $\sqrt{\beta_x}$	0.17 μm · $\sqrt{\beta_x}$	0.06 μm · $\sqrt{\beta_y}$	0.11 μm · $\sqrt{\beta_y}$
1-150 Hz	0.83 μm · $\sqrt{\beta_x}$	0.41 μm · $\sqrt{\beta_x}$	0.41 μm · $\sqrt{\beta_y}$	0.29 μm · $\sqrt{\beta_y}$

TABLE 1. Integrated beam position temporal RMS values with FOFB off and on, without moving of ID gaps. Values at a location s in the storage ring can be obtained by multiplication with $\sqrt{\beta(s)}$.

Apart from the improved integrated beam stability up to 100 Hz, the FOFB allows autonomous and independent changes of ID gaps as well as beamline optimization by the users. Tests with rapidly moving ID gaps and correctors have shown that the resulting orbit kicks are invisible to all other users, when the FOFB is active. Fig. 4 shows the improved long term stability at the SLS with the FOFB running, compared to the situation, when orbit corrections were performed by the SOFB. Each data point represents the spatial RMS values of all 72 BPMs in the feedback loop with respect to a pre-defined "golden orbit". The BPM readings have been averaged over a period of 0.32 ms, which is a quite relevant bandwidth for most of the present SLS users. While RF frequency and ID gap changes have still resulted to orbit disturbances in case of the SOFB (see left side of fig. 4), the FOFB completely rules out any orbit transients. Likewise, the remaining RMS noise drops significantly to about 0.71 µm horizontally and 0.06 µm vertically (@ ≈ 3 Hz bandwidth) due to the higher sampling and correction rate (4 kS/s) of the FOFB. Since beam position information in the SLS FOFB architecture is only distributed locally and dispersion fits in each sector are based on a total of 18 beam position readings at a rate of 4 kHz, the low level part of the feedback corrects off-energy trajectories only on a micron level. Resulting slow drifts of the dispersion orbit and horizontal mean corrector kicks are avoided by a high level beam dynamics application, which adds suitable offsets to horizontal corrector currents and RF frequency every 20 – 30 minutes. As a result, a blurring of the global horizontal spatial RMS distribution can be observed (see inlet in the lower right graph of fig. 4), which however does not affect the stability of the source points in the ID straight sections since they are dispersion free.

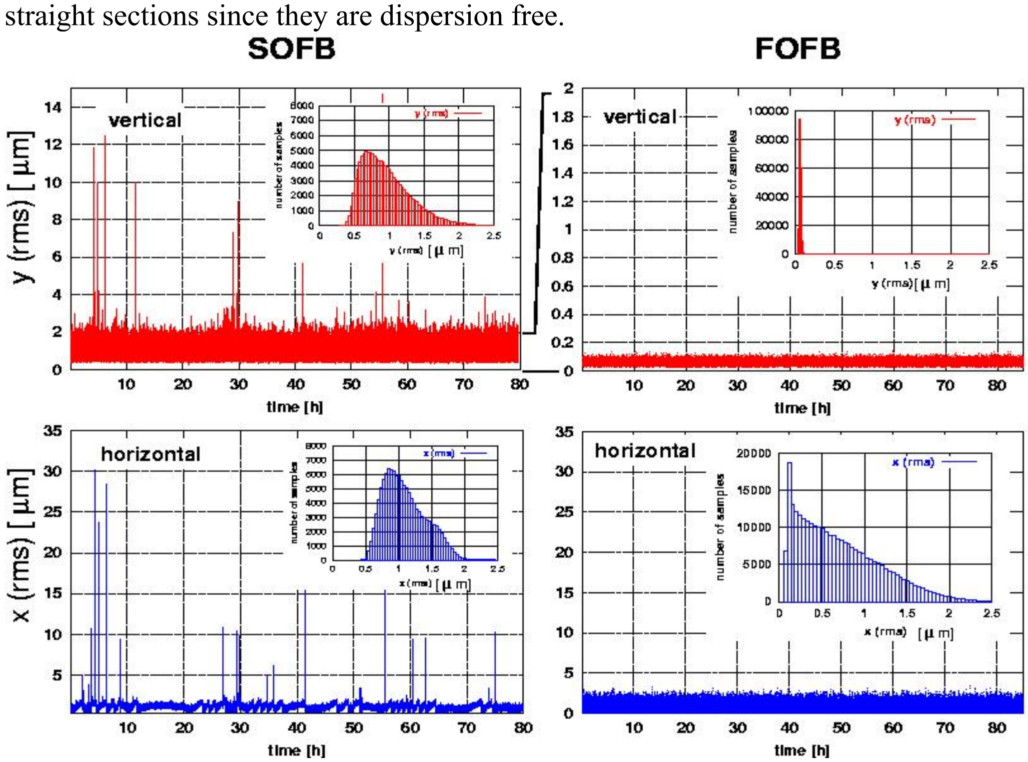

FIGURE 4. Comparison of SOFB (left side) with FOFB (right side) performance. Graphs show the horizontal and vertical spatial RMS orbits of all 72 in-loop BPMs with respect to a pre-defined reference orbit ("golden orbit") over a period of three days. Orbit disturbances due to RF frequency and ID gap changes, which are still visible on the left side (SOFB) are completely ruled out by the FOFB. The mean value of the spatial RMS orbit with FOFB is $x\,(RMS) \approx$ 0.71 µm horizontally and $y\,(RMS) \approx 0.06$ µm vertically.

Photon BPM (PBPM) readings have been taken as external references to demonstrate the efficiency of electron beam stabilization for the beamlines. Although, the PBPM signals at SLS are presently still subject to position offsets whenever the ID gaps are changed, fig. 5 shows horizontal and vertical photon beam positions on the X06S protein crystallography (PX) beamline over a measurement period of 19 h with constant ID gap. The data points are not (yet) synchronized to the DBPM readings and have been averaged over a period of 1 s.

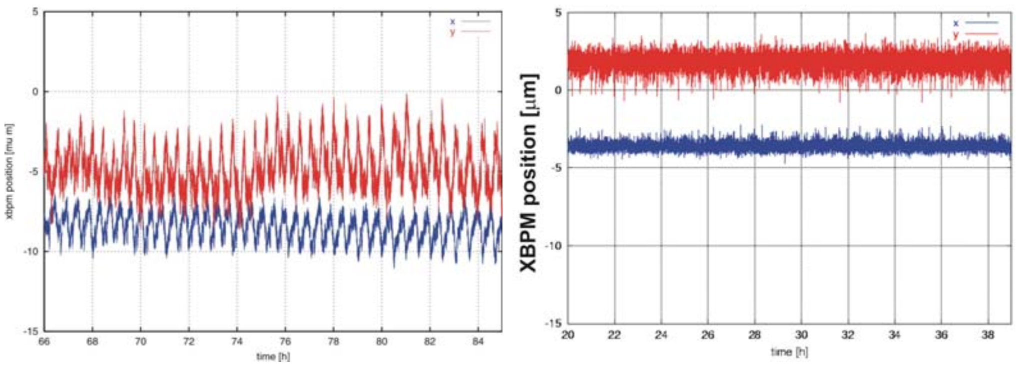

FIGURE 5. Left side: horizontal and vertical PBPM readings at the X06 protein crystallography (PX) beamline indicating photon beam stability of ± 1.5 μm peak to peak with the FOFB active. The remaining systematic oscillation of the photon beam with a ~ 45 min period has been stabilized to sub-μm RMS level at the first optical element of the beamline implementing a slow, high level feedback on the PBPM readings (right side).

The left side of fig. 5 shows the situation with the FOFB active. It stabilizes the photon beam at the location of the PBPMs about 10 m from the source point to ± 1.5 μm peak to peak. A systematic oscillation of a ~ 45 min period is left on the photon beam, which was originally suspected to be a temperature effect in the four channel DBPM electronics. However, measurements of the DBPM rack temperatures did not show any correlation with the observed systematic drifts. Just lately, the time constant of this residual oscillation could be correlated to the injection clock cycle, which constantly proceeds over the buckets to be filled in the storage ring during “top-up” operation. A corresponding bunch pattern dependency of the DBPM electronics has been demonstrated to be the reason for the remaining orbit oscillations and a bunch pattern feedback in the storage ring is presently under development to eliminate this effect. Presently, a slow, high level feedback application on the PBPM readings has been implemented resulting in sub-μm RMS beam stability at the first optical elements of the SLS beamlines (see PBPM readings on the right side of fig. 5).

MONITORING OF MEDIUM TERM STABILITY

While the FOFB has proven to stabilize the electron beam orbit at the SLS on a sub-μm level in a frequency range from ~ 0.1 to 100 Hz, medium term stability ranging from minutes to days represents a similar important feature for the experimentalists. Due to impedance optimization, the SLS vacuum system has no bellows over a length of 19 m throughout the arcs of the TBA lattice. Thus, during its design phase finite element analyses (FEA) have been performed, showing that the vacuum chamber bends significantly under thermal loads and thermal transients. As a result of these studies, it has been decided to support the vacuum chamber at the positions of the BPMs using transversely stiff supports and allowing motion in the beam direction at the same time. While a 1 mm clearance prevents any touching of the vacuum chamber and the storage ring magnets, the transverse mechanical positions of every BPM bocks in the storage ring are monitored by the so called POMS (position monitoring) system [3]. Two linear dial gauges, which are rigidly attached to the adjacent quadrupole magnets, are housing a set of optical encoders providing 0.5 μm position resolution in respect to the magnetic axis of the machine, which has been previously determined by the method of beam based alignment. As an example of the POMS performance, fig. 6 shows the measurement of the horizontal position of the 02-SE BPM block. It can clearly be seen, that the mechanical position of the BPM is changing whenever thermal transients – in this case due to beam loss and decaying beam – are present. In case of "top-up" operation providing thermal equilibrium in the storage ring no mechanical movements of BPM blocks within the resolution of the system are visible. Thus, monitoring of the BPM block positions with the POMS system allows the conclusion that even the medium term stability of the SLS under "top-up" conditions is in the μm-level.

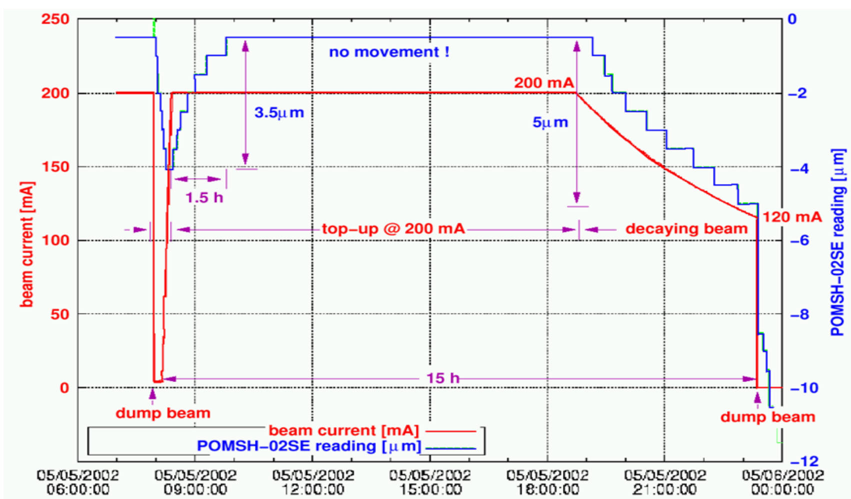

FIGURE 6. Readout of horizontal POMS sensor attached to BPM-02SE showing that the mechanical position of the BPM block is unchanged during "top-up" operation of the SLS storage ring. Only thermal transients caused by beam losses and/or decaying beam force a movement of the BPM block.

CONCLUSIONS AND OUTLOOK

The global FOFB with its distributed hardware structure is in regular user operation since November 2003 and has lead to sub-μm electron beam stability at SLS in a frequency range from ~ 0.1 – 100 Hz. Stability-wise, it has exceeded its original design parameters and satisfies the present stability requirements of the SLS users.

The regular “top-up” operation of the SLS at presently 330 mA (± 0.5 mA) provides most stable and reproducible conditions for the DBPM electronics and leaves the storage ring in a thermal equilibrium. Thus the medium term stability (from days to minutes) of the SLS, which is constantly monitored by the POMS system, resides on a µm-level as well. A residual systematic beam oscillation of ± 1.5 µm at the location of the photon BPMs has been correlated to the SLS injection cycle clock and has been shown to be a filling pattern dependence of the DBPM electronics. A slow, high level feedback application has been implemented at the protein crystallography and material sciences beamlines to correct for these oscillations, stabilizing the photon beam at the location of the first optical elements to a sub-µm level.

The commissioning of the “fs pulse slicing” beamline as well as the construction of additional bending magnet beamlines during the next year will break the symmetry of the present FOFB architecture due to additional RF and photon BPMs, which are needed to provide the required beam stability for these experiments. Therefore, an extension of the FOFB architecture is already foreseen allowing the integration of fully synchronized position readings from additional sensors on the DSP bus of the FOFB system.

ACKNOWLEDGMENTS

The achievement of beam stability on a µm-level has shown to be only possible, if all people working on the FOFB subsystems like beam dynamics, instrumentation, control system as well as electrical and mechanical engineering are open for new concepts and continuous discussion pursuing the common goal of beam stability. I would like to take the opportunity to thank all these colleagues at SLS as well as the colleagues from other light sources for many fruitful discussions and their impact on our strategies on orbit stabilization.

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