On the questions posed by Professor Robin Tucker during the GG interview, ESTEC 21 April 2015

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We appreciate the possibility given to us by SARP to provide useful material and information on the questions posed during the interview by Professor Robin Tucker. Since we may have misinterpreted some of the written *Questions* received on April 10, as well as those posed by Professor Tucker on April 21, this opportunity is extremely useful.

The files we have handed over to Luigi Colangeli just after the interview are:

- GGreport1998-2000-chapter_6.pdf
- 16 - SD-RP-AI-0629_1 GG Report on Simulators.pdf
- 14 - SD-RP-AI-0621_2 Technical report on drag and attitude control.pdf

hereafter referred to as F1, F2 and F3 respectively.

To our best understanding and recollection, the questions posed by Professor Tucker during the interview can be summarized as follows, though we change the order in which they were posed as we think it will help the overall discussion (we apologise for our own rephrasing of the questions...):

1. The dynamical model used in the simulator was not well defined, neither in the proposal nor in the *Appendix* provided to SARP on April 15 along with the *Answers*. In particular it was not clear whether it included all bodies in 3D or not.
2. The equations of whirl motions as presented in the *Appendix* were unsatisfactory (incorrect?); the equations of whirl control were not provided at all and there were no details on the PID control either.
3. The issue of possible chaotic whirl motions was not convincingly addressed.

Our best answers to these questions (in the same order) are the following:

1. File F2 is the official TAS-I document (written by Giuseppe Catastini in June 2009) on the simulators developed for GG under funding from ASI. File F3 on drag free and attitude control (written by Gianfranco Sechi in July 2009) ensures the simulator that it can rely on the required level of reduced drag acceleration. Files F1 and F2 together provide the available information on how the GG space experiment is, to our best knowledge, going to perform. Altogether, it amounts to 167 page of documentation. Note that GOCE had been launched a few months before these documents were written, that TAS-I was ESA prime contractor for GOCE, and that both Catastini and Sechi played key roles in it.

F2 and F3 refer to GG in equatorial orbit, since that was the baseline in 2009. We moved to the sun-synchronous orbit after discovering that thermal noise was much lower than expected and that we could use a laser gauge readout with sufficiently small noise to exploit the very short integration time. Thus, the 1°/ d precession of the orbit plane in sun-synchronous orbit would allow offline separation of systematics from the signal. The changes were specifically addressed during in a 2.5-month study of GG with JPL in 2010-2011, but the documents have not been re-written.

Both documents are part of the *"GG Preliminary Requirements Review Data Package (GG-PRR-Data-Pack)"*, Ref. [19] in the GG M4 proposal. This data package is quoted in the Executive Summary, where we stated: *"The GG space mission has already been studied at Phase A2 level with ASI funding in the recent past, and the data package from that study (some 30 documents submitted to Preliminary Design Review in 2009) is available to ESA, on request, without exception."*

We thought it would be unkind to SARP scientists to attach these two big documents as such. The *Appendix* was written specifically for SARP, in an attempt at helping panel members to grasp the key issues without too much work.

Though we did our best in the short time available to answer all questions, we did not succeed and *a posteriori* we must conclude that we should have provided SARP with F2 and F3 full documents. Nonetheless, on p. 5 of the *Appendix*, TABLE 1 and the following bullet list show all bodies included in the simulation and all degrees of freedom required for a 3D simulation. The total number of degrees of freedom reported in the *Appendix* was also reported in the first slide of the set devoted to the simulator in the GG presentation at the interview (Slide 28). Obviously the presentation contained more information than I had the time to cover in half an hour, and unfortunately I did not draw attention to this issue.

There is no way that all the work done for the GG simulator could be reported within the page limit of M4 proposals. It was addressed in Sec. 3.2.1 where, unfortunately, we never mentioned that the model was in 3D. We were confident in the rigor and completeness of the work performed along the lines and with the tools of GOCE, and left out this important information.

2. Successful simulations of whirl motion control in GG were first performed by TAS-I (then Alenia Spazio) in 1998-2000 under ASI funding. They are reported in Ch. 6 (see file F1) of the GG Phase A Report 1998-2000 (Ref. [1] in the *Appendix*). At that time the simulations were performed with planar translational motions and 3 degrees of freedom for all rotational motions (note that the test cylinders were coupled with rods on gimballed joints while the current coupling has changed; it is shown in pp. 26-27 of the GG M4 proposal and this is the one used in the 2009 simulator).

   Knowledge of whirl motions is obviously needed in order to design and implement their control.

   In F1 we report the equations of whirl motion for two bodies, the s/c and the PGB, under the external force due to residual drag (what remains after drag free control). This is done in pages 155-157 of F1. For each of the two bodies the equations of motion are given by (6.5): there is the elastic constant k, the offset vector $\vec{\epsilon}$, the rotating damping c_r and there is the external force $\vec{F}_{ext}$ representing the residual drag force (acting on the spacecraft and not on the PGB inside it). Fig. 6.3 makes all variables clear.

   The residual drag force is the largest force acting on the s/c, and it cannot be avoided; therefore it is important to see what is its effect on the whirl motion and how we can control it in the presence of this force. Fig. 6.4 shows that the effect of the external force is simply to displace the equilibrium position, while not affecting the growth of whirl motion.

We cannot find anything wrong with Eqs. (6.5) and with these results.

Perhaps one might argue: where is gravity? How do we know that the two bodies are orbiting the Earth? These equations are written in the non spinning satellite frame. The system is in free fall around the Earth; hence –due to the equivalence principle which, for this purpose is certainly valid– gravity is canceled. Gravity gradients (tides) obviously remain, but need not to be taken into account in this analysis because they are smaller than the residual drag, due to the fact that the relative displacements are very small. For sure, in the simulator, the Earth's gravity field and its gradient are included, but in the current analysis of how whirl motions develop and what should be done to control them, gradients would be an unnecessary complication and they would add nothing to our understanding of whirls.

These equations and Fig. 6.3 were reported in the *Appendix*, but we did not add any comments.

Moving on from Eqs. (6.5) in F1 we write Eqs. (6.9), in which an appropriate non rotating damping with coefficient C_{nr} has been added, capable of stabilizing the whirl motion, as it is known in rotordynamics.

An analytical approach to whirl motions, with a simplified mathematical model including also the conical modes, can be found in Nobili et al., NA 1998 (Sec. 3.1) and may be useful (http://eotvos.dm.unipi.it/ggweb/newastronomy/paper/article.pdf)

Secs. 6.1.12 and 6.1.13 in file F1 are devoted to the whirl control laws and to their implementation. It is true that we did not provide these equations. We assumed that the stabilization of whirls demonstrated by the simulator, and also in GGG over runs of about 1 month duration (as published in 2012) were sufficient evidence.

Concerning the question on PID control, it was reported by Giuseppe Catastini during the interview that no PID controller is used. Two lines at the end of Sec. F in the *Appendix* read: *"The control implementation adopted for the GG satellite does not rely on a PD or PID implementation, but on ad hoc devised double Fourier reconstruction of the modulating signal"*.

3. We got the impression that Professor Tucker was worried of possible chaotic whirl motions, even in absence of bearings.

   We recall that in GGG the suspensions (of lower mechanical quality than those to be used in space) routinely pass through the resonance each time the system goes from subcritical to supercritical rotation, which is certainly a considerable stress. Nonetheless, if we take care to adjust the whirl control parameters after passing the resonance, whirl is damped and we have performed runs of one month with good sensitivity that could not possibly be achieved if whirl were chaotic.

   In GG the flexures will never go through any resonance because spin up occurs with all masses are locked. Furthermore, as described in Sec. 3.1.4 of the GG M4 proposal, there are two launch-lock systems. The hard one is used only at launch, and once un-locked it will never be used again. The fine one is based on inch-worms (see Fig. 10 in the proposal) which allow us to gently reduce the relative motion of the masses –while they are being released– until these reach the level that the whirl control actuators can manage. At that point it is up to the whirl control to keep all separations within about 10 nm; see Table 6 in the proposal. In the presence of such small displacements everything is linear and we see no reason to expect chaos.

   However, should the whirl control fail, the inch worms can take care of the relative displacements of the masses until the control is fixed, and nothing dramatic will happen. Since no science measurement can be done without whirl control, some redundancy must be ensured, although we know that capacitance sensors and actuators are very reliable.