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# Objective Evaluation of the Somatogravic Illusion from Flight Data of an Airplane Accident

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**Abstract:** (1) Background: It is difficult for accident investigators to objectively determine whether spatial disorientation may have contributed to a fatal airplane accident. In this paper, we evaluate three methods to reconstruct the possible occurrence of the somatogravic illusion based on flight data recordings from an airplane accident. (2) Methods: The outputs of two vestibular models were compared with the "standard" method, which uses the unprocessed gravito-inertial acceleration (GIA). (3) Results: All three methods predicted that the changing orientation of the GIA would lead to a somatogravic illusion when no visual references were available. However, the methods were not able to explain the first pitch-down control input by the pilot flying, which may have been triggered by the inadvertent activation of the go-around mode and a corresponding pitch-up moment. Both vestibular models predicted a few seconds delay in the illusory tilt from GIA due to central processing and sensory integration. (4) Conclusions: While it is difficult to determine which method best predicted the somatogravic illusion perceived during the accident without data on the pilot's pitch perception, both vestibular models go beyond the GIA analysis in taking into account validated vestibular dynamics, and they also account for other vestibular illusions. In that respect, accident investigators would benefit from a unified and validated vestibular model to better explain pilot actions in accidents related to spatial disorientation.

**Keywords:** spatial disorientation; motion perception; otolith; semicircular canal; vestibular; computational model; pilot performance; accident investigation; aviation safety

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## 1. Introduction

On 23 February 2019, Atlas Air cargo flight 3591, a Boeing 767–300, entered a steep descent from 6000 feet and impacted terrain about 40 miles from George Bush Intercontinental Houston Airport (IAH), Houston, Texas. The airplane was destroyed, and the three crew members were fatally injured. According to the accident investigation, "the probable cause of the accident was the inappropriate response by the first officer as the pilot flying (PF) to an inadvertent activation of the go-around mode, which led to his spatial disorientation and nose-down control inputs that placed the airplane in a steep descent from which the crew did not recover" [1]. It was concluded that the first officer likely suffered from a somatogravic illusion, which in this case produced a false sensation of pitch in response to sustained longitudinal acceleration. The somatogravic illusion originates in the perceptual ambiguity between the gravitational acceleration and inertial accelerations due to airplane maneuvering [2,3]. The combination of acceleration components determines the gravito-inertial acceleration (GIA) vector, which is sensed by the otolith organs in the inner ear. In the absence of visual references, the central nervous system is challenged to distinguish between the tilt of the otolith-sensed GIA vector due to, on the one hand, longitudinal airplane acceleration and, on the other hand, the pitch of the airplane relative to gravity. As the accident airplane was likely flying in poor visibility conditions, the flight crew was susceptible to a somatogravic illusion under the influence of the longitudinal acceleration resulting from the increase in engine thrust and retraction of the speed brakes associated with the go-around [1].

Previous accident and incident reviews have concluded that spatial disorientation (SD) has had a persistent presence in commercial jet transport accidents worldwide, with roughly one per year for more than the last 20 years [4–6]. In an analysis of 15 such events that occurred during go-around [7], six of them were directly linked to the somatogravic illusion. However, conclusions about the presence of SD and its influence on pilots' flight control inputs has always relied on analyzing aircraft accelerations. A vestibular model can identify further influences from the vestibular dynamics, sensory integration, and neural processing that are involved in human motion perception. In that respect, accident investigators can benefit from a vestibular model to estimate how pilots may perceive aircraft motions. In [5], such a model was used to show that the PF in an accident linked to SD did not get any vestibular feedback on unintentional roll motion because it remained below the human perception threshold. This result illustrates that a vestibular model can help to find indications of SD illusions other than the somatogravic illusion.

In the current paper, we analyze the recorded flight data of the recent Atlas Air accident with three objective methods to determine whether the aircraft accelerations were likely to have produced the somatogravic illusion. Although the NTSB report does not provide details of such an analysis, it mentions that "the GIA vector sensed by the pilots swung dramatically aft" [1] (p. 41). This suggests that the investigators looked at the behavior of the GIA vector derived from the gravitational and airplane acceleration components in the recorded flight data. This is also how the somatogravic illusion is usually explained in textbooks (e.g., [8]). However, it is questionable how accurately the GIA vector—it being the physical stimulus—reflects the way it is perceived as pitch by the pilots.

Therefore, we compared vestibular models that contain mathematical characterizations of vestibular dynamics to the "standard" GIA vector to determine if they provide more accurate estimates of the somatogravic illusion. The two models were: (1) the "Spatial Orientation and Motion Sickness" (SOMS) model described by [9]; and (2) the "Observer" model initiated by [10] and elaborated on by [11]. Both models have been (partly) validated with empirical data on perceptual responses and have been used successfully to predict motion perception relevant for spatial disorientation. Although both models also include visual inputs to account for visual–vestibular interactions, these fall outside the scope of the current paper and will not be further discussed.

We were limited in our ability to determine conclusively which model provides the "best" estimate because we could only relate the analysis to behavioral indicators, such as the PF's control inputs and callouts. Hence, the main research question was whether there are differences between the approaches in the way they predict the somatogravic illusion. In addition, we were interested to see if the predicted illusion could account for the pilot pitch inputs. We also discuss the shortcomings of the current models and suggest improvements. Our ultimate objective is to develop a unified, validated method that can support accident investigation; not only for the somatogravic illusion, but for an objective determination of any vestibular SD illusion in flight.

### *Research on the Somatogravic Illusion*

Here we summarize some experimental studies which provide insight in the magnitude of the somatogravic illusion. In an early in-flight study, blindfolded subjects reported perceived tilt during forward accelerations up to 2.0 $\mathrm{m/s^2}$ and decelerations up to $-2.8\ \mathrm{m/s^2}$ [3]. The study showed that the somatogravic illusion occurred above a threshold of 0.2 $\mathrm{m/s^2}$. With accelerations above approximately 1.1 $\mathrm{m/s^2}$ and with decelerations below $-1.7\ \mathrm{m/s^2}$, 100% of the subjects reported a perception of pitch.

The detrimental effect of the illusion on erroneous "corrective" pilot control inputs has often been associated with catapult launches during dark nights [12]. Using a human centrifuge, [13] simulated a 40 m/s$^2$ aircraft catapult launch by rotating the subject in addition to the centrifuge rotation to keep the combined resultant tangential and centripetal acceleration along the subject's $x$-axis. The subjects reported on changes in perceived (horizontal) eye level, a visual derivative of the somatogravic illusion referred to as the oculogravic illusion. The illusion appeared to be present in 11 out of the 12 subjects tested. In another centrifuge study, [14] already observed the oculogravic illusion at tilts of the GIA vector of 10 deg (i.e., centripetal accelerations of 1.8 m/s$^2$). As a special note on the oculogravic illusion, it can be surmised that the apparent shift of the visual scenery may add to the illusory perception of bodily tilt, which makes the somatogravic illusion hard to ignore, potentially even more so when pilots are looking inside the cockpit.

As shown by [9], the temporal behavior of the somatogravic illusion induced by centrifugation can dramatically be affected by the semicircular canal response to the centrifuge onset (which is not present during accelerated longitudinal flight). In an attempt to get rid of this confounding sensory input, [15] studied the somatogravic illusion in a variable radius centrifuge, spinning up the subject with their heads on the central centrifuge axis until a constant angular velocity of 80 deg/s was reached. After the rotation sensation had faded, which typically happened within 60 s, the cabin was shifted 2.15 m outward while keeping the subject facing the rotation center. This resulted in a centripetal acceleration of 4.1 m/s$^2$ corresponding to a tilt of the GIA vector of 22.5 deg. All subjects experienced the somatogravic illusion with an average magnitude that was about equal to the tilt of the GIA vector and a standard deviation of about 8 deg. Translating a standard deviation of 8 deg to a (healthy) population, and assuming a normal distribution, this would imply that over 99% of all people would experience a somatogravic illusion under these conditions.

Altogether, these findings indicate that the somatogravic illusion is difficult to ignore when visual references are lacking, and that it can occur with acceleration magnitudes associated with transport aircraft.

## 2. Materials and Methods

### 2.1. Vestibular Models

Details and block diagrams of the SOMS and the Observer model can be found in [9] and [11,16], respectively. Both models consider inputs from the otolith organs and the semicircular canals: the two sub-systems that constitute the equilibrium organ in the inner ear. The otolith organs respond to the GIA, which is the vector sum of the gravitational acceleration ($\mathbf{g}$) and inertial accelerations associated with linear motion ($\mathbf{a}$); hence, $\mathbf{GIA} = \mathbf{g} + \mathbf{a}$ (note that GIA in this vector addition is marked in bold, while in the text GIA is just phrased as abbreviation). The semicircular canals respond to angular accelerations of the head and are thus insensitive to a constant, or slowly varying, angular velocity (such as a sustained aircraft turn). In the frequency range of natural head movements, the response of the semicircular canals is, however, proportional to angular velocity (see, for example, [17]). Hence, both vestibular models use angular velocity as an input signal for the semicircular canals.

Mathematically, the behavior of the semicircular canals can be described by a high-pass filter that transmits relatively quick changes in head rotation and filters out low-frequency angular motions. A high-pass filter also predicts the decay in the rotation sensation, which is typically reported by blindfolded subjects in response to an angular velocity "step" (i.e., a vestibular stimulus consisting of a sudden increase in angular velocity that is then held constant). For roll and pitch rotations, the time constant of this decay has been estimated between 4 and 7 s [18]. In the SOMS model, this time constant is set to 4.2 s, and in the Observer model, it is 5.7 s. Note there is a longer time constant for yaw rotations to account for a neural process known as "velocity storage" [19,20], which prolongs the perception of yaw rotations. However, because yaw rotations play a minor role in the control of fixed-wing aircraft, we here focus on pitch and roll rotations.

There is one, more fundamental, difference between the models with respect to the perception of (roll and pitch) rotations about a non-vertical axis. Whereas the predicted perception in the SOMS model is purely based on the characteristics of the semicircular canals, the Observer model also takes otolith inputs into account, which respond to the changing orientation of the head relative to gravity. As a consequence, the Observer model predicts a more sustained perception of roll or pitch rotations than the SOMS model, which is shown in Figure 1**.** for a roll stimulus. Figure 1 also shows that, because of the decaying response during prolonged rotation, we perceive an after-sensation of rotation in the opposite direction when the rotation stops, which is larger in the SOMS model output compared to the Observer model output. In flight, this after-sensation may occur after a slow roll motion and is known as the post-roll illusion [19].

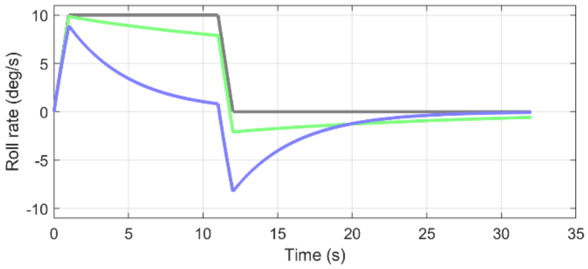

**Figure 1.** Model output of the SOMS model (blue line) and the Observer model (green line) in response to a sudden increase in roll rate (gray line) up to a constant rate followed by a deceleration back to zero. This shows that the semicircular canals respond to the onset of rotation (i.e., acceleration) and that this response subsides while rotation continues at a constant rate. As the response has waned, the deceleration at the stopping of the rotation causes an output below zero, which corresponds to a roll sensation in the opposite direction (i.e., the post-roll illusion).

With regard to the input signals to the otolith organs, both models assume that the peripheral otolith organs respond to a wide frequency range, which can be represented by a simple unity matrix [17]. However, the models differ in the way the otolith-sensed GIA is disambiguated into an (internal) estimate of gravity. A key assumption in the SOMS model is that our brain "knows" that Earth gravity is constant and that accelerations due to head motion are variable [17]. Hence, it is assumed that the neural process to determine an internal estimate of gravity from the GIA can be approximated by a low-pass filter. The time for this low-pass filter was set at tau = 2 s based on [15]. As gravity is constant in an Earth-fixed reference frame and the GIA is sensed in a head-fixed reference frame, the latter must first be transferred into Earth coordinates before applying the low-pass filter. This transformation is performed by a rotation matrix using angular velocity information from the semicircular canals. The result must be rotated back into head coordinates by the inverse matrix to obtain the internal, head-referenced estimate of gravity.

In contrast to the SOMS model, the Observer model does not explicitly use frequency segregation to disambiguate the otolith stimulation into gravity (i.e., tilt) and linear acceleration (i.e., translation). Instead, the model hypothesizes that the brain generates expected sensory measurements, enabling the computation of "sensory conflict". This framework is inspired by the engineering estimation structure of the classic Luenburger observer [20] and is implicit in Kalman filtering [21]. Specifically, it is hypothesized that the brain uses internal models of sensory dynamics and physical laws to produce the expected sensory afferent signals [10,22]. These are compared to produce sensory conflict signals that are then weighted with a gain. These gains serve as free parameters, defined once by the modeler to explain spatial orientation perception across a range of motion paradigms [11].

While the Observer model does not explicitly utilize frequency segregation, the canal–otolith integration produces similar behaviors for many motion paradigms (i.e., low-frequency otolith stimulation is accurately predicted to be perceived as tilt). As shown in Figure 2, both models predict that the longitudinal acceleration (gray line in the upper plot), representing a static takeoff run, results in a brief perception of forward motion (colored lines in the upper plot) followed by a sustained perception of nose-up pitch (colored lines in the bottom plot). This pitch-up sensation reflects the somatogravic illusion. The green line in the middle plot shows the perceived angular velocity component computed by the Observer model based on the rotating GIA vector on the otoliths, which is not present in the SOMS model. This illusory angular velocity explains why the Observer model predicts a larger somatogravic illusion than the SOMS model (bottom plot).

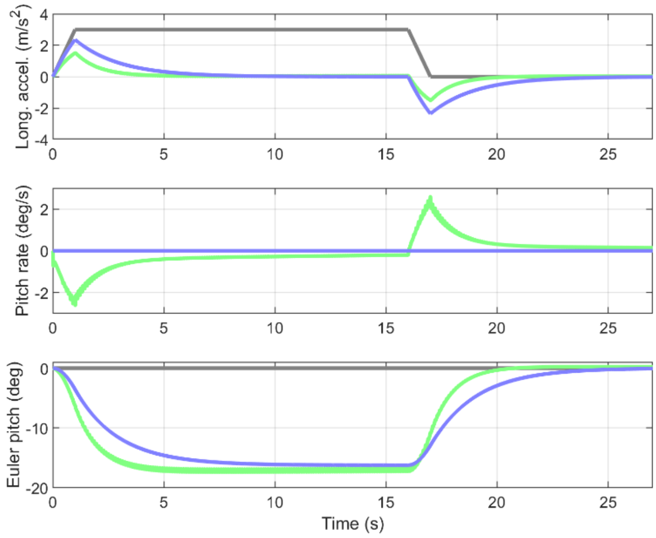

**Figure 2.** Output of the SOMS model (blue lines) and the Observer model (green lines) in response to a stepwise increase in longitudinal acceleration (gray line in **upper panel**) representative of a "static" takeoff run, where the engines are set at takeoff thrust with the brakes on and the aircraft starts to accelerate as soon as the brakes are released. The **upper**, **middle**, and **lower plots** show, respectively, longitudinal acceleration, pitch rate, and Euler pitch angle.

### 2.2. Recorded Flight Data

We retrieved the original data files of Atlas Air flight 3591 from the public NTSB docket (https://data.ntsb.gov/Docket?ProjectID=99013, accessed on 2 August 2022). The comma-delimited data file obtained from the Flight Data Recorder (FDR) is listed as Document #63 and is presented as Attachment 1 to the Flight Data Recorder Specialist's Factual Report (Document #62), which explains how the tabular data should be read. In addition, the latter document presents plots of the important recorded flight parameters during the entire flight, as well as during the last three minutes of the flight. As the critical events in the recorded data begin with the apparently inadvertent engagement of the take-off/go-around (TO/GA) mode, about 33 s before the end of the recording, we used the final 40 s of the FDR file. The data were pre-processed by inversion of the y-component to be compliant with the coordinate system used by the vestibular models, in which linear motion is positive in the forward, left, and upward directions and, correspondingly, rotational motion is positive for right-ear down roll, nose-down pitch, and leftward yaw. The GIA vector was derived from the data by combining the linear acceleration and gravity components from the FDR and determining the direction of that vector. Although it is not mentioned, we assumed that the accelerations were measured at the aircraft center of gravity. To avoid additional complexity and assumptions, we did not convert the accelerations to the cockpit level.

## 3. Results

### 3.1. Comparison of Perceived Pitch in Relation to Control Inputs

The upper part of Figure 3 presents the final 40 s of the time histories of the perceived pitch angle computed by each of the three models (GIA in red, SOMS model in green, and Observer model in blue) in combination with the actual recorded airplane pitch (black). The vertical dashed line identifies the point of TO/GA activation.

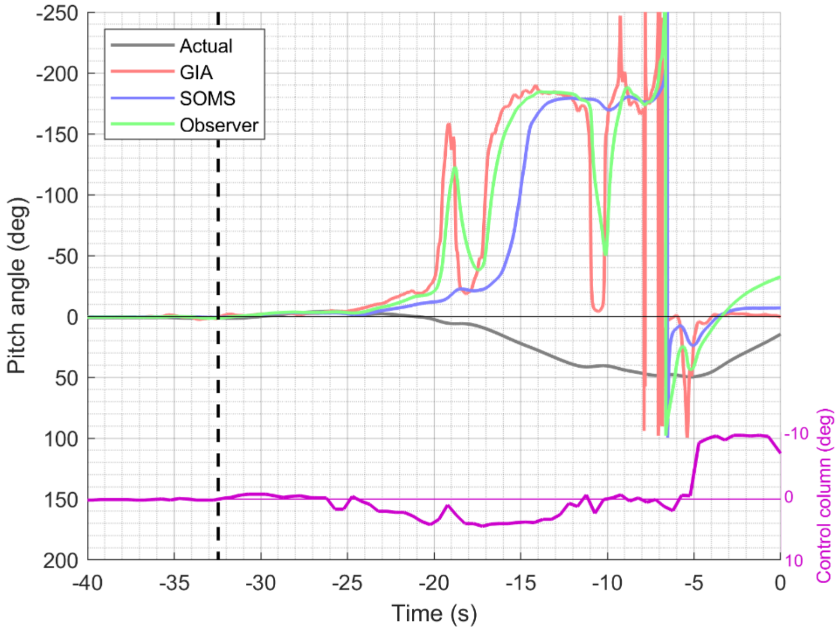

**Figure 3.** Time histories of the actual pitch angle (black), the computed GIA (red), and the perceived pitch predicted by the SOMS model (blue) and the Observer model (green), respectively. Note that the corresponding y-axis (on the left) is shown inverted to match the common aviation reference frame in which pitch up is positive. The x-axis shows the time in seconds until the end of the flight data recording. The vertical black dashed line indicates the TO/GA activation. The bottom part of the graph shows the time history (in purple) of the control column corresponding to the y-axis shown on the right (in degrees; positive is push down).

A first glance at Figure 3 shows that—for most part of the investigated period—all three computation methods predict that, after an initial pitch-up perception that reflected actual airplane pitch, the perceived pitch angle increased dramatically, even up to 180 deg, which corresponds to an "inversion illusion" [23], whereas the airplane was actually pitching down, reaching a maximum of about 50 deg. In general, the Observer model output seems to follow the GIA more closely than does the SOMS model output. In particular, between t = −22 s and t = −18s, both the GIA and Observer model outputs show a fairly short-lived increase in perceived pitch angle, reaching about 150 deg pitch up (i.e., almost an inversion illusion). This peak is much less pronounced in the SOMS model output. Looking further, both models and the GIA predict a second, more sustained inversion illusion between t = −18 s and t = −7 s, although the SOMS model output lags a few seconds compared to the GIA and Observer model outputs. However, between t = −11 s and t = −9 s, both the GIA and the Observer model outputs show a sharp decrease in this inversion illusion, while the SOMS model output remains relatively constant during that period.

The time history of the recorded position of the left column (bottom part of Figure 3) shows a first indication of pitch-down input around t = −26 s; i.e., about 6.1 s after the TO/GA activation. Interestingly, the perceived pitch predicted by all three methods starts to deviate from actual pitch at t = −25 s; i.e., one second after the first pitch-down input. For much of the remainder of the recording, the PF kept pushing the column forward, with brief interruptions at t = −19 s and t = −12 s. According to the accident report [1] (p. 44), the captain started pulling back on the left column 15 s after the activation of the TO/GA mode (hence, at t = −19 s in our time histories). However, his actions were not enough to fully correct the PF's pitch-down control input. Finally, at t = −5 s, there is a strong pitch-up control input, indicative of the crew's final recovery attempt, which was too late to prevent impact with terrain. During these final 5 s, the GIA angle returns to zero, whereas both vestibular model outputs are still above zero (and the Observer model output still increasing). Note that the accident report indicated that the EGPWS alerting ("pull up" or "too low, terrain") did not occur during the steep dive as it typically does for these types of events.

Although Figure 3 shows dramatic discrepancies between the perceived and actual pitch representative of a somatogravic illusion, the time scale is too coarse to determine how the illusion developed or, more importantly, how it was triggered. In order to evaluate this, Figure 4 depicts the first ten seconds of the same time histories from Figure 3. Here we see that, in the second after TO/GA activation (at t = −32.5 s), the GIA vector tilts backward to about 2 deg, which corresponds to a forward acceleration component of about 0.37 $m/s^2$ (not shown). In contrast, both vestibular models show a more gradual increase in perceived pitch, and three seconds later both model outputs are aligned again with the GIA vector. Interestingly, all three methods show an increase in perceived pitch before the actual pitch starts to increase (which is at t = −31.3 s). However, according to the time history of the control column, this initial perception of pitching up did not trigger a pitch-down input until six seconds later (around t = −26 s). It thus seems that, during this period, the difference of about 2 deg between perceived and actual pitch was too slight to induce a pitch response.

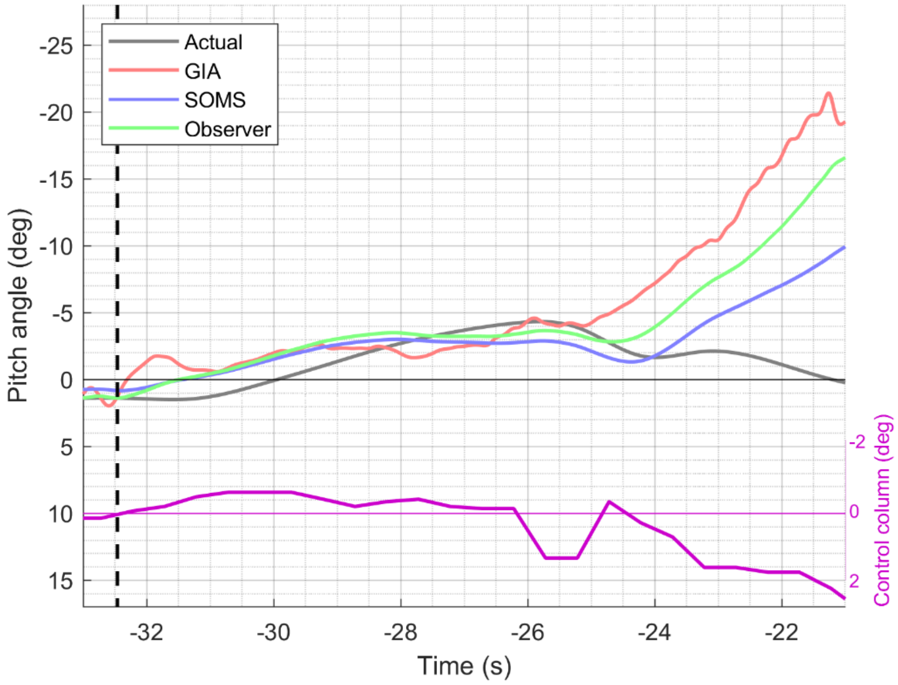

**Figure 4.** The same time histories as in Figure 3 but zoomed in between −33 and −21 s.

Figure 4 shows a marked pitch-down input at t = −26.1 s, which lasts for 3 s before a more sustained pitch-down input is given. As a result, the actual pitch angle immediately starts decreasing. However, this is followed by an increase in the perceived pitch computed by all three methods, albeit with different time delays: there seems to be no delay in the GIA vector, whereas the Observer model output lags about 1 s and the SOMS model output lags about 2 s. Before this increase, the perceived pitch predicted by both models temporarily decreases, representative of the transient semicircular canal response to the pitch-down rotation. Interestingly, the start of the first pitch-down input does not seem to correlate with a marked increase in the model outputs, although the GIA vector seems to oscillate in the three seconds before the pitch-down input, but only in the order of 2 deg.

### 3.2. Magnitude of the Somatogravic Illusion

Figures 3 and 4 show that, while the PF's pitch-down input continued, the GIA vector kept tilting backwards. Such a strong tilt in the GIA vector cannot have been caused by the longitudinal acceleration of the airplane but was largely determined by the unloading of the aircraft. The blue line in Figure 5 depicts the z-component, or "load factor", of the GIA as a function of time. This shows that the load factor quickly decreased below 1 g, even to negative g, in correspondence to the PF's strong pitch-down inputs. The load factor dropped below zero twice: first, a brief period around t = −19 s corresponding to the first inversion illusion observed in Figure 3; and second, a longer period corresponding with the second and more sustained inversion illusion. This indicates that, during large fluctuations in the tilt of the GIA, this angle is largely driven by the GIA's x-component because the z-component becomes very small or even negative.

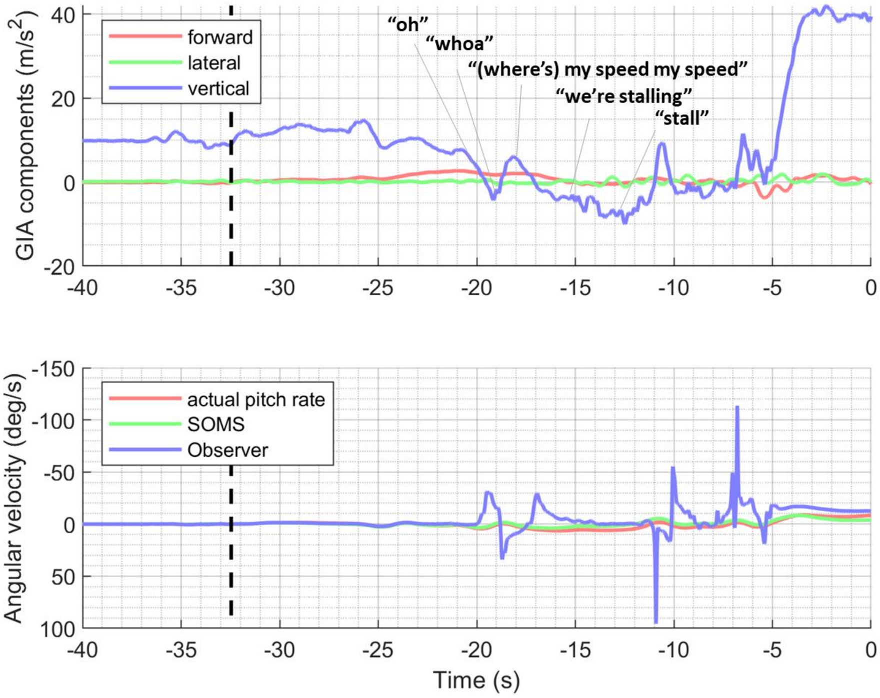

**Figure 5.** Time histories of the recorded GIA components (**upper panel**, m/s$^2$) and actual and predicted pitch rate (**lower panel**, deg/s). The PF's callouts in the **upper panel** were copied from Appendix D within reference [1].

It is questionable whether this is a realistic representation of how people perceive pitch in such situations, as previous studies on the somatogravic illusion mostly involved accelerations larger than 1 g, which did not induce changes in the tilt of the GIA anywhere close to an inversion illusion. Interestingly, the occurrence of the inversion illusion has been investigated in an aircraft [2]. In this study, the flight profile started with a longitudinal acceleration of 0.15–0.25 g from 200 to 250 Kts in level flight, followed by a gentle pull into a 250 Kts climb for 30 s and then a push to achieve a negative vertical acceleration of −1.0 g for 6 s. The verbal responses of 9 out of 13 blindfolded subjects indicated that they perceived a sensation of inversion. Thus, the duration of the second episode of the inversion illusion in Figure 3 could have been long enough for the pilots to have experienced an inversion illusion similar to that predicted by the two models. In any case, we can probably surmise that the perception of pitch is not very accurate in these dynamic conditions and that the Atlas Air pilot may have been totally confused about what his pitch angle was. In this respect, it is interesting to note that the PF's recorded exclamations (shown in Figure 5) indicate that he had the impression that the airplane was stalling in the phase where the load factor was below zero. It is unlikely that this feeling was caused by the airspeed itself, since that was actually increasing when he made these callouts [1] (p. 2). This suggests that the feeling of unloading may also have been perceived as "falling" instead of as an inversion illusion.

## 4. Discussion

The PF in the Atlas Air 3591 flight inadvertently engaged TO/GA and, after 6.1 s, made nose-down inputs that continued for 20 s before nose-up inputs were made; these late nose-up inputs were insufficient to prevent the airplane crashing into terrain. Our analysis of the perceived pitch angle showed that, according to all three computational methods, it is likely that the pilot experienced a somatogravic illusion during the final 20–30 s of the flight, which concurs with the conclusion of the accident report [1]. However, the three methods did produce differences in terms of the dynamic behavior of the perceived pitch angle, especially during quick changes of the GIA: in these phases, the pitch angle computed by the GIA itself (obviously) fluctuates directly with its direction. Instead, the outputs of both vestibular models lagged 1–2 s behind changes in the GIA and filtered out relatively high-frequency changes. The Observer model output followed the GIA more closely than the SOMS model output, which can be attributed to two factors. First, in the Observer model, the perceived angular velocity contains a component derived from otolith afferents, whereas in the SOMS model, it only depends on semicircular canal afferents. Second, the SOMS model uses a low-pass filter for the frequency segregation of the otolith-sensed GIA, which makes the model more conservative during rapid changes in GIA direction.

The fluctuations observed in the GIA vector in the Atlas Air flight were linked to strong unloading of the airplane, which caused the load factor to decrease below 1 g and even below 0 g. Most experimental studies on the somatogravic illusion have been performed in a human centrifuge with load factors well above 1 g. Hence, there are little experimental data available to conclude how people perceive (changes in) their pitch orientation when the GIA is quickly reduced or even inverted. Interestingly, from spaceflight we know that the vestibular system does not provide useful information about our orientation in weightlessness, so that astronauts orient themselves predominantly with visual cues. Studies in partial-gravity parabolic flights have shown that this vestibular loss of orientation perception occurs when gravity drops below 0.3 g. At such low gravity levels, most subjects did not recognize the gravity vector as a reference for verticality and could not determine their orientation [24,25]. However, the gravity levels during these flights were well-controlled and relatively stable, in contrast to the erratic behavior of the GIA in the final minute of the Atlas Air flight.

Without empirical data on how people perceive their pitch orientation during a dynamic maneuver, such as the go-around, especially when unloading also occurs, we cannot decide which of the three computational methods provides the best approximation of how the somatogravic illusion presented itself to the accident pilots. All three methods predict an "overpitch" sensation, but none of the methods seem to explain the pilot's initial pitch-down control input, as the first indications of the somatogravic illusion appear 1–2 s after the aircraft pitch starts declining. This suggests that the somatogravic illusion was not the cause of the PF's first pitch-down control input but subsequently may have been the consequence. From the moment the PF started pitching down, the aircraft pitch-down motion became progressively larger, which may have further exaggerated the somatogravic illusion (even up to an inversion illusion). Alternatively, the PF's callouts suggest that, in the phase where the load factor was below zero, he erroneously inferred that the aircraft was stalled. This sensation may provide an additional explanation of why he continued to provide pitch-down control inputs in a (hypothetical) attempt to recover from a stall.

We should acknowledge the limitations of the vestibular models with regard to the interpretation of their predictions. As mentioned before, one such limitation is that the models are largely validated based on well-controlled experimental studies that have been performed in 1 g environments (e.g., on a rotating chair [26]) or in hyper-gravity environments (e.g., in a centrifuge [27]). Consequently, we cannot assume that any currently available computational method (including the GIA) accurately predicts how people perceive their orientation in a less-controlled flight environment; particularly, when the airplane ultimately is nose-diving to the ground. Maybe all we can say about such flight phases is that the vestibular feedback becomes wildly confusing and that the pilots may eventually lose their sense of orientation completely. The models likely hold more validity during the transition from relatively straight and level flight to extreme vestibular stimulation, during which SD likely develops; thus, it is critical to understand the pilot's orientation perception.

Another uncertainty in the determination of the somatogravic illusion is that, while our current analysis focused on the perceived pitch angle, we do not know to what extent the illusion depends on the perceived angular velocity. It does not seem unrealistic to assume that a pilot may start control inputs for pitching down as soon as he or she perceives the airplane's attitude to change or "rotate" away from the desired attitude. Interestingly, the Observer model takes the "tilt rate" of the GIA vector into account, which partly explains why the predicted somatogravic illusion was somewhat larger than predicted by the SOMS model. It is also unclear how the perception of pitch is affected by the vertical accelerations perceived at the flight deck due to loading and unloading. It is likely that experienced pilots have learned that pitching up or down is associated with a feeling of loading or unloading, respectively, especially in large aircraft where the cockpit is located a few meters in front of the center of rotation. In addition, in our analysis, we have not considered the possibility of G-excess during high load factors [27]. However, in the Atlas Air flight, the load factor only increased well above 1 g in the final five seconds of the flight, which is well beyond the point where somatogravic illusion must have confused the pilots.

Nevertheless, vestibular models account for the experimental finding that, in the absence of semicircular canal stimulation, the perceived pitch induced by linear acceleration generally lags behind changes in GIA. Hence, we would recommend that accident investigators use a vestibular model, rather than the GIA, when analyzing FDR data for the possible occurrence of spatial disorientation. In fact, the vestibular models also account for perceptual phenomena and spatial disorientation effects other than just the somatogravic illusion. This has previously been demonstrated for the post-roll illusion [19] and undetected roll motion [5].

## 5. Conclusions

All three computational methods showed evidence for a somatogravic illusion that could lead to pitch-down inputs, although there were differences in their predicted dynamic behavior. For two reasons, we recommend using a vestibular model, and not just the GIA direction, to evaluate spatial disorientation from flight recordings. First, vestibular models take into account perceptual dynamics, which are validated based on experimental studies. Second, vestibular models also apply to SD phenomena other than the somatogravic illusion.

Although the SOMS and Observer models are built with different architectures, their outputs were surprisingly similar for the Atlas Air data. Future research should attempt to fill the gap in pitch perception under unloading and near 0 g conditions and aim at harmonizing the model outputs even more by validating the model parameters so that we work towards one unified accident investigation model.

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