Two+ Page Essay about Possible Cause of Boeing 737 MAX 8 Failure

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Of course, it is much too early to be certain of the cause of the Boeing 737 Max 8 failure; but it is not too early to, perhaps, make an educated guess based on some related experience and some knowledge of technology trends. My speculation about the cause of the failure is related to possible presence of GPS spoofing (or denial of the GPS signal sought because of jamming) and how it may adversely affect INS behavior when an autopilot is activated or invoked.

While baro-altimeters or radar-altimeters had historically been used to "stabilize the vertical channel" of an airborne conventional Inertial Navigation System (INS) from the 1960's through to the mid 1980's:

[1] William S. Widnall, Prawn K. Sinha, "Optimizing the Gains of the Baro-Inertial Vertical Channel," *AIAA Journal of Guidance, Control, and Dynamics*, Vol. 3, pp. 172-178, 1980. https://arc.aiaa.org/doi/10.2514/3.55966

[2] William S. Widnall, Arthur E. Bryson, "Comment on 'Optimizing the Gains of the Baro-Inertial Vertical Channel'," *AIAA Journal of Guidance, Control, and Dynamics*, Vol. 3, pp. 286-288, 1980. https://arc.aiaa.org/doi/pdf/10.2514/3.55989.

[3] E. M. Copps, G. J. Geier, W. C. Fidler, P. A. Grundy, "Optimal Processing of GPS Signals," *Navigation: Journal of the Institute of Navigation*, Vol. 27, No. 3, pp. 171-182, Fall 1980.

More recently, GPS has been offered as an alternative sensor candidate to be used to stabilize the vertical channel of an airborne INS (*sometimes in conjunction with an altimeter*):

[4] Jaewon Seo, Jang Gyu Lee, Chan Gook Park, "A New Error Compensation Scheme for INS Vertical Channel," *IFAC Proceedings*, Vol. 37, No. 6, pp. 1119-1124, 2004. https://pdfs.semanticscholar.org/7366/6bbb75dbb3e71e5314fe1e2f52a1e2b686af.pdf.

Despite others recently experiencing GPS jamming and/or spoofing world-wide (example: Year-long ocean cruise finds GNSS interference…everywhere - GPS World: https://www.linkedin.com/pulse/year-long-ocean-cruise-finds-gnss-gps-world-dana-a-goward/, https://www.gpsworld.com/year-long-ocean-cruise-finds-gnss-interference-everywhere/ , https://insidegnss.com/spoofing-incident-report-an-illustration-of-cascading-security-failure/, https://www.defensenews.com/global/europe/2019/03/08/norway-alleges-signals-jamming-of-its-military-systems-by-russia/, https://static1.squarespace.com/static/566ef8b4d8af107232d5358a/t/5c99488beb39314c45e782da/1553549492554/Above+Us+Only+Stars.pdf , https://www.c4reports.org/aboveusonlystars , many have previously warned us about this important vulnerability that we should all be concerned about:

[5] Daher, J. K., Harris, J. M., Wheeler, M. L., "An Evaluation of the Radio Frequency Susceptibility of Commercial GPS Receivers," *IEEE AES Systems Magazine*, Vol. 9, No. 10, pp. 21-25, October 1994.

[6] Pinker, A., Smith, D., Walker, D., "Jamming the GPS Signal," *Proceedings of the 55th Annual Meeting of the ION*, Cambridge, MA, 28-30 June 1999.

[7] Littlepage, R. S., "The Impact of Interference on Civil GPS," *Proceedings of the 55th Annual Meeting of the ION*, Cambridge, MA, 28-30 June 1999. (He warned us early on! His presentation was more explicit than his paper. He was truly concerned.)

[8] Kerr, T. H., "Further Critical Perspectives on Certain Aspects of GPS Development and Use," *Proceedings of 57th Annual Meeting of the Institute of Navigation (ION)*, pp. 592-608, Albuquerque, NM, 9-13 Jun. 2001. http://www.tekassociates.biz/FurtherCriticalperspectivesonGPS2001.pdf.

However, others are confident that these threats can be defeated by utilizing sufficient additional resources, such as Differential GPS (DGPS):

[9] White, N. A., Maybeck, P. S., DeVilbiss, S. L., "Detection of Interference/Jamming and Spoofing in a DGPS-Aided Inertial System," *IEEE Trans. on Aerospace and Electronic Systems*, Vol. 34, No. 4 pp. 1208-1217, Oct. 1998.

While some had pushed/lobbied for use of exclusively tightly-coupled INS/GPS systems early on for obtaining optimal accuracy (in presumed benign environments):

[10] https://www.gpsworld.com/expert-advice-loose-coupling-and-whats-wrong-with-it/, the historical warning trend (since the mid 1980's by Dr. Triveni N. Upadhyay's [and by Dr. Duncan Cox's] Mayflower Communications and, concurrently, by others at [now defunct] Intermetrics, Inc., e.g., Dale Kline) had sought use of loosely-coupled systems to be more robust and resistant and resilient in the face of subsystem failures or presence of jamming/spoofing. Hopefully, these newer approaches will be even more robust to jamming and spoofing in the future:

[11] Kim, K. H., Lee, J. G., Park, C. G., "Adaptive Two Stage Extended Kalman Filter for a Fault-Tolerant INS-GPS Loosely Coupled System," *IEEE Trans. on Aerospace and Electronic Systems*, Vol. 45, No. 1, pp. 125-137, Jan. 2009.

[12] https://insidegnss.com/petite-new-spoofing-detector-aims-to-protect-gps-gnss-receivers-in-drones-vehicles-even-cell-phones/

Regarding the Boeing 737 MAX 8 failure, the pilots reported experiencing a dramatic pitch down (or up) when the autopilot was activated. Such behavior would be expected if an

improper anomalous value of GPS vertical (due to GPS spoofing) were being used in a vain attempt to stabilize the vertical INS channel. Other mechanisms may be at work as well, such as, lack of sufficient critical damping of oscillations in the autopilot. We will have to wait until analysis of the data from the Boeing 737 MAX 8 black boxes is complete. In the meantime, we recommend that at least 3 sensors be used instead of the current 2 external sensors. In this way, if there is disagreement between two sensors, a third could be used to perform voting if the original two are at odds and disagree. With 3 sensors, one can also use mid-point-select.