

## ***Interactive comment on “Potential radio frequency interference with the GPS L5 band for radio occultation measurements” by A. M. Wolff et al.***

**A. M. Wolff et al.**

amw0031@auburn.edu

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Dear Referee #2,

Thank you for your very helpful response. Your comments have furthered my understanding with the material and improved my writing ability. Below are my responses to the specific comments that were noted in your review.

Sincerely, -Alex

Referee comments noted with page numbers. Author response noted with \*\*

Specific comments and technical corrections:

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Page 4530, line 7: "...a means" -> "...a source". "A means" implies that it is something one wants to achieve. I don't suppose that is what is meant here.

Page 4530, line 8: Suggestion to reformulate: "This study presents results from a Systems Tools Kit (STK) simulation..."

Page 4531, line 16: "This resulting ..." could be reformulated to "The post correlation C/N0 is a popular metric ..." with a reference at the end of the sentence. But perhaps even better just to skip (or move somewhere else) everything from "This resulting ..." to "...can be witnessed". It would make a better connection to the previous sentence.

Last paragraph of the Introduction: A reference such as "(see next section for more information on GPS RO)" or "As described in the next section..." would be appropriate when explaining about GPS RO already here.

Page 4532, line 8: I don't think it is correct to say that "GPS has stimulated an evolution in weather forecasting technology". The technology has not changed because of GPS, but GPS RO has contributed to the advance of weather forecasts. Maybe this could be written differently.

\*\*These five suggestions have been taken into account and the changes will be reflected in the first revision.

Page 4532, line 9: "RO technique leverage ..." I'm not sure what 'leverage' means in this context.

\*\*Leverage as a verb is defined in the following way: "to use (something valuable) to achieve a desired result." The text referenced notes how the RO technique utilizes inherent traits of the GPS network (stability and coverage) for its advantage.

Page 4532, line 17: "refraction of the signal causes a delay...". Delay refers to time; when talking about the phase it would be more accurate to call it "excess phase".

Page 4532, line 19: Maybe replace "into desired values for" with "the vertical distribu-

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tion of". Refraction depends on these variables, but in humid regions of the atmosphere they cannot be derived individually from the observed refraction alone.

Page 4532, line 22: To be consistent, first letter in "ratio" should be capitalized.

Page 4532, line 23: "(SN(R+I))" seems odd. R does not stand for Noise, it stands for Ratio. But is the abbreviation necessary? It is not used later. I don't understand how "reduced Signal..." would allow for lower atmosphere soundings. Shouldn't it be "increased Signal..."?.

Page 4533, line 3: Like the current COSMIC mission, COSMIC-2 is also a joint Taiwan/US mission, and that should perhaps be mentioned here. To be correct it should be referred to as Formosat-7/COSMIC-2. Also the Metop-SG satellites to be launched several years from now will carry RO receivers relying on E5/L5 signals. The situation is potentially more critical for Metop-SG, since they will not in addition track the GPS L2C signal (as COSMIC-2 will). Also it could be noted that future RO with Galileo is relying on E5a (which is at the same carrier frequency as GPS L5, but the signal structure is different).

Page 4533, line 7 (also in other places in the paper): As a matter of style, starting a sentence with an acronym should be avoided.

\*\*These four suggestions have been taken into account and the changes will be reflected in the first revision.

Page 4533, line 14-16: Is "interference" correct/sufficient terminology (by which I understand the superposition of two or more waves resulting in a new wave pattern). Wikipedia gives several definitions of interference, one of which is called "adjacent-channel interference", another one "co-channel interference". Would any of those describe it better? As I understand (and I admit that my understanding is limited here), it may not be the interference itself that is the problem, but the large input power at the RF front-end. Is that correct?

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\*\*In this case, the co-channel interference is the better description. The GPS L5 signal was created with full knowledge of the potential DME/TACAN interference as both systems share the same frequency spectrum. Adjacent channel interference is used to describe systems on different frequency channels but their sidelobes are not filtered to the point such that they do not impact each other. But it was assumed the GPS and DME/TACAN could co-exist with minimal impact for terrestrial or aviation applications since: (a) the GPS signal power is sufficiently low enough not to interfere with DME/TACAN; and (b) the pulsed nature of the DME/TACAN signals coupled with the limited number of DME/TACAN stations a terrestrial or aviation user would see would have a small degradation (2-6 dB) on the GPS L5 signal processing.

Page 4534, line 11: Could the statement that "In the United States alone there are approximately 203 DME or TACAN ground stations ..." be supported by a reference?

\*\*A table has been made detailing each relevant station including the station's name, symbol, transmitting frequency, latitude, and longitude. This table will be included in the revision.

Page 4534, line 15: Please discuss briefly why RO receivers have bandwidths of +/-10 MHz or wider, and relate it to the fact that a RO receiver sampling rate of about 50-100 Hz is sufficient for data collection. See Sokolovskiy (Radio Science, vol. 36, 483-498, 2001) and Bonnedal et al. (GPS Solutions, vol. 14, 109-120, 2010) and cite as appropriate. There is also a recent paper on interference from terrestrial sources and its impact on RO measurements from the Metop-A satellite (Isoz et al., Radio Science, vol. 49, doi:10.1002/2013RS005243, 2014).

\*\*The GPS L5 signal structure requires 20 MHz of spectrum with a center frequency of 1176.45 MHz to capture 92% of the transmitted signal energy and beyond 20 MHz the received signal power is greatly limited. Therefore, it is consistent that 20 MHz is used as the standard bandwidth for the GPS L5 signal.

What is the impact of interference in such a wide bandwidth (+/-10 MHz) when the GPS

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signal is subsequently filtered in the receiver with a bandwidth of only 100 Hz around the carrier (plus shift from Doppler model in the receiver)? Is the subsequent filtering relevant for the possibility (or avoidance) of receiver saturation?

\*\*50-100 Hz is the output measurement rate for a RO receiver. Given the signal processing, this is approximately the maximum rate that independent information can be provided.

\*\*Due to the spread spectrum nature of the system, the 20 MHz signal is processed in a much smaller bandwidth post correlation with the code division multiple access (CDMA) spreading code. This aids in reducing the impact of the interfering signal by spreading that energy across a wider bandwidth which is then filtered to the post correlation bandwidth. However, the power levels from the DME/TACAN broadcast are not minimized to a sufficient extent through this spreading operation.

\*\*For the simulation, only DME/TACAN stations within the +/- 10 MHz about the GPS L5 1176.45 MHz center frequency were considered as a conservative approach. In reality, many of the early stage RF components, such as the low noise amplifiers and filters will be of much wider bandwidth given the center frequency. So it is very likely that additional DME/TACAN stations outside of the 20 MHz bandwidth considered will be observed by the receiver.

The Doppler model in the receiver takes into account the shift due to the atmosphere and the satellite velocities (see Sokolovkiy, 2001). The Doppler shift from satellite velocities could shift the received L5 signal by about 10-30 kHz, depending on the geometry. Would/could DME/TACAN stations transmit within 10-30 kHz of the L5 frequency? Would this be relevant for the possibility of receiver saturation, or is the problem merely that the incoming power in the +/-10 MHz band-width around the carrier from DME/TACAN stations is larger than a RO receiver can cope with?

\*\*The Doppler shift for an orbiting receiver in LEO was not considered but it is likely to both add/subtract DME/TACAN stations adjacent to the band approximately at the

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same level.

Page 4534, line 17: Please explain a bit more what 'receiver saturation' means. Is this design dependent? Can it be quantified and put into context with the simulations later on in the paper? The provided reference (ITU, 1998) gives some explanation, but it is unclear if the numbers there can be directly applied to a RO receiver system.

\*\*It is design dependent and there are multiple phases within a receiver in which the interference can be problematic. The first stage amplifier, for example, in most GPS receivers is not designed for high power handling and is optimized for a low noise figure. This tends to work well since the GPS signal level for terrestrial users is below the thermal noise floor. However, the DME signals are of high power and can drive certain amplifier designs into saturation given the signal energy seen and the recovery time of these can vary from part to part. Even if the amplifiers stay linear, the resulting additional signal energy from the DME/TACAN transmissions will continue through the RF path into later signal conditioning/processing impacting the automatic gain control (for multibit receivers) as well as the underlying signal processing. Quantifying these levels, particularly given the variation in receiver designs, is beyond the scope of this paper but is under investigation, at least in the form of a case study provided specific receiver architecture.

Page 4534, line 18: "Furthermore, the directive orientation of the receiver antenna pattern ... increases the total number of DME stations". I'm not sure I understand this. I agree that the directional pattern of the RO antenna adds to the concern, because the gain is then the largest possible, but why would it lead to an effective increase in the total number of DME stations seen by the receiver? Wouldn't it decrease the total number seen, exactly because the antenna patterns are highly directional.

\*\*This should, indeed, be reworded. I meant that the DME stations witnessed would be a greater cause for concern due to the directive nature of the gain pattern. This will be clarified in the revision.

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Page 4535, line 5: 38 deg in azimuth relative to what? To North? What was the azimuths to the DME/TACAN stations?

\*\*Azimuth is measured clockwise from the North. The exact angles relative to each DME/TACAN station are unknown. Figure 3 can be used to visually gain an understanding of these positions. The exact angle is not used in any calculation but rather to demonstrate the directive orientation of the receiver antenna.

Page 4536, line 5: "The author of" could be skipped, just starting the sentence "Roturier (2001) ...".

\*\*This change will be reflected in the first revision.

Equation 1 (besides the correction pointed out by R. Notarpietro in the on-line discussion): In the text, please give the values for  $P_e$ ,  $G$ ,  $\lambda$ , and  $d$  that were used to obtain  $P_1 = -107$  dBW. Is 'effective radiated peak power' the same as 'DME radiated peak power'? If it is, use only one term; if not, explain the difference.

\*\*The values are as follows:  $d = 246$  NM,  $P_e = 40$  dBW,  $\lambda = 25.5$  cm,  $G = 0$  dB. These values will be noted in the text after the first revision. There is no difference between those two terms. I tried to use the modifiers to clarify and distinguish from the received power but it seems it had the opposite effect. I will simplify the language in order to clear up this issue.

Page 4537, line 1-3: Please make clear that Formosat-3/COSMIC is a constellation of 6 satellites. I suppose only one of them was used in the simulations. Which one?

\*\*Formosat-3 FM4 was the exact satellite used for the study. It will be noted that this is one of 6 other satellites in the constellation.

Page 4537: Was the true gain pattern for the COSMIC satellite antenna taken into account in the simulations (it is not mentioned)? In Figure 7, I would not expect much of a signal when the receiver is right above the DME station, because the RO antenna does not point in that direction. The signal would also depend on the viewing azimuth angle

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from the receiver. Was this taken into account? I assume also that the gain pattern of the receiving antenna would depend on the frequency. If the true gain pattern was not taken into account, then please discuss the possible implications for the simulation results in the text, or make new simulations with a more realistic gain pattern. The gain pattern of the COSMIC satellites RO antennas are quite narrow in elevation and limited in the azimuth, but I'm not able to quantify this. Possibly scientists at UCAR/CDAAC can give more information. The person at UCAR to ask would be Bill Schreiner. Information might also be available at the COSMIC website ([www.cosmic.ucar.edu](http://www.cosmic.ucar.edu)).

\*\*The gain pattern for the COSMIC antenna was modeled by Erin Griggs, a Doctoral student at the University of Colorado – Boulder. Her work is cited in the references. The modeled gain pattern closely resembles the true pattern of the receiving antenna and should be sufficient for such an analysis. The simulation included the proper viewing angles in elevation and azimuth for both the fore and aft receiving antennas. These angles are 27.38 degrees and 27.16 degrees in elevation for the fore and aft antennas respectively. These values will be included in the revision.

Page 4537, line 24: "interfering" instead of "inferring". Page 4537, line 25: "signal" instead of "station".

Page 4538, line 2: "the number of stations" instead of "a plot of the stations".

\*\*These two changes will be reflected in the first revision.

Page 4538, line 3: Please provide a table with relevant information on the 203 DME stations (at least station name and coordinates). This would be necessary in order to reproduce the results if anyone wants to do that. Perhaps a reference to where such information is obtained would suffice.

\*\*A table has been made detailing each relevant station including the station's name, symbol, transmitting frequency, latitude, and longitude. This table will be included in the revision.

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Page 4538, line 3-7: Is the true gain pattern for the COSMIC satellite antenna taken into account here? If not, could this have influence on the conclusion that "receiver saturation remains as a possibility" (Page 4538, line 13)? How many interfering stations with a transmitting power of -125 dBW would it take for receiver saturation to occur? Is it realistic to think that all 203 stations are operating at the same time?

\*\*The same pattern described above was used for this simulation. STK does not indicate saturation so further measures are needed to determine if this scenario would occur. This preliminary study has provided simulated values for the interference and therefore will allow further work to demonstrate if these values would cause saturation. More specifically, the saturation of the receiver is dependent upon the design of the receiver and, in particular, the early stage front end components. In addition, the analog radio frequency elements are prone to saturation due to the inclusion of interference in conjunction with the standard noise levels. With that said, the continuation of this work will delve into the specific problem of receiver saturation with real world case studies.

\*\*It is realistic to think that the DME stations are all operating at the same time. However, referring to the introduction on the DME system, the pulse duty cycle for a single station is about 4.32%. In effect, this means that a single receiver will only see a single DME station 4.32% of the time. From a receiver's perspective, these pulses would overlap due to the multitude of transmissions from different DME stations thereby causing a probability for saturation. The exact percentage of time interfered that is needed to saturate a receiver is unknown but future work is planned to provide an answer.

Page 4538, line 14-16: It is not clear if the results in Figure 9 comes out of the above described simulations, or if it is obtained separately. In Figure 8 the maximum number of stations is 76, in Figure 9 the curves extend (at least) to 90 stations. Please describe in some detail how the percentage of time was calculated (such that the results in principle can be reproduced).

\*\*These two figures were obtained separately. For Figure 9, assuming all of the DME

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stations are independent, the percentage of time at least one DME station is interfering with the receiver is calculated through probability. The exact calculation is as follows:  $1 - (1 - \text{duty\_cycle\_DME})^{n_{\text{DMEall}}}$  where  $n_{\text{DMEall}}$  is the number of total DME stations and the  $\text{duty\_cycle\_DME}$  is the percentage of time the DME station is transmitting. This result is simply plotted as a function of the number of DME stations and Figure 9 is the result.

Page 4539, line 5: "...at any given point in time...". This is not consistent with Figure 8, which shows that there are more than 70 stations for only about one minute in the time interval around 6-7 minutes.

\*\*You are correct and this statement is not worded appropriately. I will clarify the statement to read as a maximum of 82 stations interfering at some point in time.

I suggest a bit more explanations in the Figure captions: Fig. 1: Is this a real measurement? What/when/where? What is the envelope curve?

\*\*This figure is referenced in the caption. The author notes that the measurement was taken at the Green Bank Telescope. No further details were provided but this structure is well defined and can be replicated in any sample including DME interference. I was not able to locate an exact reference for a DME envelope curve.

Fig. 2: Day and time of measurement? What is the 'Magnitude' the magnitude of?

\*\*This data was taken on October 21, 2012 at 17:30 UTC. The magnitude in decibels describes the Fourier transform of the time domain into the frequency domain as seen by the helical antenna after post processing. The figure shows a 20 MHz bandwidth with 1176.45 MHz as the center frequency. The curved nature of the plot is due to the filter design.

Fig. 3: What is the scale? What is the distance between stations?

\*\*This figure was used to gain an understanding of the direction and relative placement of the stations. This image was captured within STK. For scale, the straight line

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distance between Pikes Peak and the Denver Mile High TACAN station is about 72 miles.

Fig. 4 and 5: Day and time of measurement (for Fig. 4 this would make it clear if it is the same measurement as in Fig. 2)? Antenna orientation?

\*\*This data was taken on October 21, 2012 at 17:30 UTC. Figures 2 and 4 were taken from the same measurement from the helical antenna. Figure 5 was taken from the Trimble dish (hemispherical) at the same time. The helical antenna was pointed 38 degrees in the Azimuth clockwise from North.

Fig. 6: Is it antenna gain? Write what the approximate values of the colors are if it is not possible to plot a color bar.

\*\*It is indeed gain. I can provide a plot of the gain pattern as provided by dB Systems Inc. This company has been referenced for the use of this pattern within the simulation. This plot includes gain values plotted against the elevation angle.

Fig. 7: Is it the mean of the power over time? What is the location of the DME station?

\*\*STK utilizes a communication link in order to establish the value of received power. The location of the DME station is 39.8125 degrees latitude and -104.661 degrees longitude. This location resembles the Denver Mile High VORTAC facility.

Fig. 8: Where is the satellite at time = 0? (North Dakota?). Where is it at time = 25 min? Please provide information that can identify the flyby (i.e., COSMIC satellite ID, date and time). Such information is important if someone wants to try to reproduce the simulation results.

\*\*I have recreated the simulation over the course of 20 minutes on January 8th, 2013 from 16:02:21 UTCG to 16:22:50 UTCG. The satellite is the same FORMOSAT-3 FM4 as discussed previously. At its peak, the receiver encountered 82 DME stations with received power levels above -125 dBW. The updated plot will be included in the revision.

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Figs. 7, 8, and 9: Write that it is simulated data. Generally, I'm not asking for discussion in the captions (discussions belong in the main text as it is), but information that relates directly to what is seen, such that the figures can be easily understood without too much reference to the text.

\*\*This will be noted in the revision.

Fig. 4 and 5: 'Amplitude' is missing a unit.

\*\*Volts have been provided as the units

Fig. 6: At the top of the figure it says with very small letters 'FOR UNFUNDED EDUCATIONAL USE ONLY'. Has it been checked if it is okay to use the figure in journal publications? Is there a legal issue that the AMT journal should be aware of here? Could the text be removed (if it is okay to remove it)?

\*\*I conducted this study as a summer research project which was not funded. I spoke directly with AGI concerning the matter and they confirmed that I am able to use any figures derived from the STK program.

References: Bastide et al.: Gps and e5a/e5b should perhaps be in capital letters.

\*\*Capitals will be shown in the revision.

Griggs et al.: "...IROWG-2m". Why the "m"?

\*\*I am unsure why the 'm' was included. A Google search on the title brings up the correct Powerpoint. The 'm' will be removed to avoid confusion.

Ostermeier, J.: Not able to locate it using Google scholar.

\*\*This is not a scholarly article but rather a product page from Rohde and Schwarz. A Google search yields the correct document.

Van Dierendonck: Journal information is given as "Proceedings of...". Other references to papers in the same journal (Bastide et al.; Kim and Grabowski) does not include the

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respective proceedings volume, but just says "J. Inst. Navig.". I do not know which way AMT wants, but it should at least be consistent.

\*\*"Van Dierendonck" will be changed to stay consistent with the other references. "J. Inst. Navig." will be used to denote the proper journal.

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Interactive comment on Atmos. Meas. Tech. Discuss., 7, 4529, 2014.

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