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Manuscript Title: Evaluation of atmospheric profiles derived from single- and zero-difference excess phase processing of BeiDou System radio occultation data of the FY-3C GNOS mission
Authors: Weihua Bai, Congliang Liu, Xiangguang Meng, Yueqiang Sun, Gottfried Kirchengast, Qifei Du, Xianyi Wang, Guanglin Yang, Mi Liao, Zhongdong Yang, Danyang Zhao, Junming Xia, Yuerong Cai, Lijun Liu, and Dongwei Wang

We thank the referees very much for the constructive comments and recommendations and for the overall positive rating that this is a significant scientific paper. We thoroughly considered all comments and carefully revised the manuscript accounting for most of them. In addition, we carefully complemented these revisions with a range of further improvements throughout the manuscript text in the spirit of the comments.
Please find below our point-by-point response (in form of italicized, blue text) to the reviewers' comments (in form of upright, black text), *inserted below each comment.*

Response to Anonymous Referee #1's comments

1 General Comments

This article presents atmospheric profiling results derived from radio occultation of satellites in the BeiDou constellation over three months, as processed by single- and zero- differencing algorithms. The derived bending angles and refractivity profiles are compared to results from the ECMWF and radiosondes collocated geospatially and temporally with the profiles from the GNOS instrument.
This paper is well organized and does a good job of describing the processing methodologies. The resulting BDS profiles are fairly consistent with both other radio occultation measurement results from the ECMWF and localized radiosondes. The results are encouraging in both the use of ultra-stable oscillators for radio occultation collection instruments (zero-differencing), and the use of the BeiDou signals as remote sensing sources for future atmospheric sensing satellite missions. I only have a few specific comments and suggestions that I'd like to see further expanded upon in the revision.

Thank you.

2 Specific Comments

The authors mention, early in the paper, that the GNOS receiver is capable of collecting both GPS and BDS data. However, I am slightly confused as to whether any GPS data were used in your single/zero-differencing studies. You make a distinction on Page 6 that the term "GNSS" refers to both GPS and BDS satellites, but it seems like only BDS satellites are used for the occultation measurements, and perhaps GPS is just used for timing? It would be interesting to the reader to compare occultation results from your same algorithms, but with GPS data over the same time and spatial intervals.

Ok, though it is a challenge to get sufficient co-located BDS and GPS radio occultation (RO) profiles in our current setup, we now performed some comparative RO data processing of BDS vs. GPS satellite observations by using the single-/zero-differencing algorithms as well. We note that evaluations of the retrieved GPS-only RO data using single-differencing algorithms have been presented by some previous papers already, so that is why this paper focuses on the BDS RO data validation. We included one BDS vs. GPS intercomparison figure now in section 3.2., which we find to exhibit reasonably high consistency. Of course, further improvements and a detailed intercomparison analysis of the GPS and BDS RO data is a very interesting study for us as well, and we plan to do it by an extra paper.
And yes, the GPS is used for timing in the BDS data processing, as described in section 2.1.

Another related point, I am curious as to why your results are negatively biased from both the ECMWF and radiosondes. The authors make a comment as to the differences in the vertical geo-locations of the profiles in comparison to the reference data, but it is odd that all the different types of BDS satellites (GEO, IGSO, MEO) are negatively biased. Again, if the authors were to process GPS data from the same times/locations with their single/zero-differencing algorithms, it could be another way to validate their methodologies and results.
The negative biases are already quite small but, yes, we agree we should be able to further reduce them in future. Currently we consider they are likely caused by a residual error in the excess phase processing and we work to further improve this processing.

The authors use radiosonde measurements within a +/- 1 deg lat-lon/ +/- 1 hour collocation criterion to validate an RO event for part of their analysis. This range can be on the order of a 200 km x 200 km box, over the course of an hour. Do the authors have an explanation or reference to the stability of the atmosphere over these spatial and time ranges?

Thanks, its a good question. Actually, the ± 1 degree lat-lon and ± 1 hour criterion was our initial collocation implementation, and we used it at the beginning of GNOS data validation. We have re-checked our programming codes, and confirmed that the temporal and spatial criterion of comparison between the GNOS BDS RO observations and the radiosonde reference data is within ± 1 hour and a circle with radius of 200 km around the radiosonde location. So we have corrected the explanation of the collocations accordingly.
Regarding the reasonable stability of the atmosphere over such collocation distances, we have now included Hajj et al. (2004) and Anthes et al. (2008) as references, since therein some discussion of representativity errors as a function of collocation distances is conducted.

3 Technical Corrections

Page 3, lines 13-14: the word "satellites" is repeated
Ok, corrected.

Page 3, lines 20-21: These new GNSS navigation satellites, together with planned LEO missions, will offer many more RO observations.
Ok, done.

Page 3, line 22: : : : onboard for the first time: : :
Ok, done.

Page 3, line 29: will have GNOS on board as well, similar : : :
Ok, done.

Page 3, line 30: The definition for the acronym GRAS is defined on page 16, should be where it is first used.
Ok, done.

Page 4, line 1-3: This description is a bit confusing. You mention three antennas on the instrument, then an antenna for the processor that has a stable phase center. Is this one of the three antennas? Or an additional antenna? Please consider rewording.
It is one of the three antennas, but not an additional antenna. The 'as well as' has been revised as 'in which'.

Page 4, line 6: Can you quantify "large"? Perhaps by the number of days or occultations
Ok, done. The 'large' has been revised as '4-year'.

Page 4, line 16: Should " GPS" be changed to "GNSS"? Single differencing may have been limited to GPS in your references, but here you use GNSS elsewhere in the same sentence.
Thanks, it should be 'GPS', since this specifically refers to the GPS 'selective availability' (SA).

Page 4, line 21: Can you reword "started to be used"?
Ok, we now say "was started to be used"

Page 4, line 24-25: : : :by an ultra-stable oscillator that, so far, was only available for GRACE : : :
Ok, done.

Page 4, line 29: So far, BDS can provide good regional coverage : : :
Ok, done.

Pages 4-5, lines 31, 1-2: : : : GNOS satellite received signals from five geostationary orbit (GEO) satellites, five inclined geosynchronous orbit (IGSO) satellites, and four medium earth orbit (MEO) satellites to conduct the radio occultation measurements.
Ok, done.

And throughout the paper, don't redefine GEO, IGSO, and MEO. Define the first time, and use the acronyms thereafter.
Ok, done.

Page 5, line 7: Remove the word "anyway"
Ok, done.

Page 8, lines 6-7: : : :as the basic equation and adopt Eq. (2) as the auxiliary equation.
Ok, done.

Page 9, line 2: Reword "comparing with" (could use "as compared to")
Ok, done.

Page 9, line 6: : : : constellation, as with the current BDS. In addition, zero differencing will likely : : :
Ok, done.

Page 9, lines 6-10: Please consider splitting this sentence into multiple sentences.
Ok, done; split into two sentences.

Page 9, line 11: In the zero-differencing approach, we employ: : : (the term Zero-Differencing is used previously in the paper. If you want to use it as an acronym, please define earlier).
Ok, done.
Page 9, line 12: "GPS" should be "GNSS", right?
Ok, corrected.

Page 9, line 21: When you say that the processing chooses the GNSS satellite with highest elevation angle, are you using both GPS and BDS satellites for single-differencing? Please clarify.
Currently, in our single-differencing data processing, only BDS satellites are used as reference satellites for BDS occultation, similarly only GPS satellites for GPS occultation. We clarified this in the text now.
Page 10, line 4: For both B1 and B2, the elevation angle appears to be more like 12 deg where the carrier phase errors are less than 2 mm.
Right, as shown in Figure 3, for both B1 and B2, the elevation should be 12 deg, where the carrier phase errors are less than 2 mm. As well as, at 10 degree both the B1 and B2 carrier phase errors are less than 2.2 mm. Actually, we use the elevation 10 degree as the reference satellite selection criterion, so we have revised the 2 mm to 2.2 mm in the manuscript.

Page 13, line 10: It looks like you might be missing a reference here.
Thanks, was left as a typo, corrected.

Page 13, line 12: MEO is already defined previously in the paper.
Ok, corrected.

Page 16, lines 4-5: Should be Allan deviation (ADEV), not Allen variance.
Ok, corrected.

Response to Anonymous Referee #2's comments

This paper presents results from the "GNOS" radio occultation (RO) measurements aboard the Chinese FY-3C satellite. It is shown that BeiDou GNSS observations, analyzed in single-differencing (SD) and zero-differencing (ZD) mode, produce bending angle and refractivity profiles of equivalent quality, when compared to ECMWF and co-located radiosonde data. In addition, due to the non-uniform global coverage of the current BeiDou space segment the ZD data set includes about 20% more events compared to the SD set because occasionally suitable BeiDou satellites providing the reference link were not available within the receiver's antenna field of view. Furthermore, a unique feature of the BDS system is that the signal transmitters are placed into three diverse orbits (MEO, IGSO, GEO). The present study convincingly shows that these orbit differences significantly modify the zonal and meridional distribution of RO events, but have no appreciable impact on the quality of the derived atmospheric profiles.
This well-written paper is a valuable contribution to the present knowledge on single versus zero-differencing RO analysis and I definitely recommend publication with some minor modifications described below.

Thank you.

General comments:
As emphasized by the authors the successful application of zero-differencing is made possible by the presence of an ultra-stable oscillator driving the GNOS instrument. It would be instructive to illustrate the performance of this clock by providing clock offset statistics. These could be extracted from the results of the FY-3C precise orbit determination.

Ok, it's a good advice, a detailed comparison analysis of the ZD and SD algorithms is a very interesting study point for us as well, and we plan to do it by an extra paper. For this paper, we preferred to give a concise algorithms description and focus on our initial FY-3C GNOS data evaluation and validation.

The comparisons of SD and ZD with ECMWF and radiosonde data are instructive and illuminating. In addition, the direct comparison between SD and ZD bending angle profiles would be worthwhile to consider, in order to substantiate the hypothesis that no biases between the SD and ZD results exist. If possible, I would encourage the authors to add a corresponding figure in the revised paper.

Ok, it's a good idea to show the direct comparison between SD and ZD bending angle and other retrieved profiles to substantiate the consistency of the SD and ZD results (but not the hypothesis of strictly no biases between the SD and ZD results, we believe, because if the LEO satellite clock is stable and accurate enough, the ZD results should be with higher accuracy than the ZD results, theoretically).
On the other hand, the topic of this paper is 'evaluation of atmospheric profiles derived from

single- and zero-difference excess phase processing of BeiDou System radio occultation data of the FY-3C GNOS mission', but not comparison analysis of ZD and SD algorithms.
Therefore, we preferred to keep the comparisons of SD and ZD with ECMWF and radiosonde data so far, since those figures are very helpful to provide an initial evaluation and validation of the SD and ZD retrievals in a scientifically reasonable way. Moreover, the readers somehow can see the level of consistency of the SD and ZD retrievals through these comparison figures.
Considering the main topic and space limitation of this paper, we therefore preferred to keep the current comparison strategy and figures (and leave rigorous SD, ZD intercomparisons as next steps of refined analyses).

Specific remarks and questions:
Page 3, lines 21ff:
"One of these LEO missions is China's GNss Occultation Sounder (GNOS) onboard first time on the FengYun 3 series C satellite (FY-3C), [...]."
For completeness I suggest to add the reference
Bai, W. H., Sun, Y. Q., Du, Q. F., Yang, G. L., Yang, Z. D., Zhang, P., Bi, Y. M., Wang, X. Y., Cheng, C., and Han, Y.: An introduction to the FY3 GNOS instrument and mountain-top tests, Atmos. Meas. Tech., 7, 1817–1823, 10.5194/amt-7-1817-2014, 2014.
Ok, done.

Page 4, lines 6–7:
"So far, a large dataset of FY-3 GNOS RO observations has been obtained." If I understand correctly, GNOS measurements aboard FY-3C started in September 2013. Thus, as of now the available data set should cover more than 3.5 years. I suggest to add a comment clarifying the decision to restrict the data analysis to the time period of three months between October and December 2013.
Thank you for this suggestion. Right, the available GNOS RO data set is more 3.5 years now. We used the first three month GNOS BDS RO data set in this paper because this period is the GNOS in-orbit testing time, and we have done lots of evaluation and analysis using this dataset. And in our opinion a 3-month GNOS BDS RO dataset is sufficient for in-orbit testing and this initial BDS RO validation paper. Future more climate-oriented analyses will use longer data records.

Page 6, lines 9ff:
"Specifically, in this study, we use the BDS satellite data as orbital data inputs and outputs, while time-wise also using GPS time for the processing of the BDS data." I'm not sure I understand this sentence. Is GPS time used for time-tagging of GPS as well as BDS observations? Please explain.
Yes, the GPS time is used for time-tagging of GPS as well as BDS observations, as described in Section 2.1.

Page 6, eqn. (1), page 7, eqn. (2), and elsewhere:

To avoid a potential misunderstanding, I suggest to define _ta as the LEO clock error (offset) at the time of signal reception and similarly _tb as the GNSS clock error (offset) at the time of signal transmission. With this change there is no need to regard _ta and _tb as functions and the function arguments in brackets (which might be confused with brackets marking an algebraic expression) could be dropped.

Ok, done. We have revised the related equations following this criterion, for the clock terms with only a subscript 'a' and only a superscript 'b' or 'c', since we agree this anyway clearly indicates reception time and transmission time. And for the terms with both the subscript 'a' and superscript 'b' or 'c', we just kept the simple argument '(t_r)' to make sure we indicate the allocation to reception time.

Page 7, lines 13ff:

"The GNSS satellite orbits (positions and velocities) and the GNSS clock offset estimates [...] are provided by the International GNSS Service [...]." IGS orbits are provided in a terrestrial reference frame. Here, a (quasi-)inertial trueof-date frame (page 5, section 2.1 "Basic algorithm of the excess phase processing") is used. For clarity, I suggest to add a remark indicating that a corresponding frame transformation has been applied.

Yes, in our processing, the GNSS satellites' position and velocity information came from IGS orbit products, and then transferred all the position and velocity from ITRF to TOD (ECI) coordination system. We have added such a remark.

Page 8, eqn. (7) and (8):

Which one of the two equations is used in the actual processing?

Equation (7); we have added this in the text now.

Page 9, lines 19ff:

"In order to use that specific reference satellite that most likely has the best signal quality and lowest ionospheric influence, our FY-3C GNOS processing chooses the GNSS satellite with highest elevation angle as the reference satellite."

From Bai et al. (2014) (see reference above) I had assumed that the decision which satellite to track as reference is already taken at the receiver level and not during data processing. Second, it would be interesting to note if the reference satellite is tracked by the occultation or zenith antenna. In the latter case SNR at high elevation angles is expected to be higher at the expense of an additional attitude dependence which must be corrected for. Please clarify.

Yes, for the FY-3C GNOS, the reference satellite is determined by the software onboard the satellite, and it selects the GNSS satellite with the biggest elevation as a reference satellite. The reference satellite's signal is received by the positioning antenna.

We have clarified this in the text now.

Page 9, lines 19ff:

"In practice, less than 0 deg means that there is in fact no reference satellite in view and [...]"

At a (sun-synchronous) orbit height of about 840 km (reference) satellites at elevation angles down to 27_ could indeed be visible. Please clarify and/or rephrase the sentence.

Ok, done.

Page 10, line 24:
"In our data processing, a quality control algorithm has been used." I suggest to quote the fraction of RO events removed by quality control.
Ok, done.

Page 12, lines 15ff:
"The target domain for the comparative statistical analysis is from 5 km to 35 km height [...], since commonly the data quality above 35 km and below 5 km is less good, due to the ionospheric effects and tropospheric multipath effects, respectively [...]" I assume that the data retrieval is based on geometric optics and wave optical methods (CT, FSI) have not applied. Please clarify.
Our RO data processing system from excess phase onwards is based on the ROPP software. So similar to ROPP, our data retrieval is mainly based on the geometric optics (CT), while below 20 km height, both the geometric optics (CT) and wave optical method were used.

Pages 25 & 26, Figs. 6 & 7:
From the figure inserts it appears that the analysis is based on the intersection of the SD and ZD data sets and that the intersection contains less events than both, the SD and ZD data set. Why are there 192 (if I counted correctly) events found in the (quality-controlled) SD data set, which did not make it into the ZD set? I suggest to add a clarifying remark.
Ok, clarifying remark added in the fig. caption.

Page 26 & 27, Figs. 7 & 8:
Why is geopotential height instead of geometric height used as vertical coordinate?
Please clarify.
We used the geopotential height for Figures 7 and 8, because the data obtained from the ECMWF model and the radiosonde observations used the geopotential height as the vertical coordinate.

Technical corrections:

Page 7, eqn. (2):
Ok, done.

Page 7, eqn. (3):
and the three bracketed expressions need to be squared.
Ok, done.

Page 7, eqn. (4):

I suggest to replace the horizontal bars in eqn. (4) (rb;c and vb;c) by a more conventional notation indicating vectors

Ok, done.

Page 8, eqn. (6):

Here, in contrast to eqn. (4), the horizontal bar seems to differentiate between transmitter and receiver dipole vector. I suggest to clarify the notation.

Ok, done.

Page 13, line 10:

There appears to be a reference missing (empty bracket).

Ok, was a typo left, corrected.

Response to Anonymous Referee #3's comments

This paper introduces, in a comprehensive way, the data processing of the first Beidou based Chinese radio occultation mission FY-3C GNOS and 3-month data were used for the study/data processing. The two strategies of data processing investigated are zero-differencing and single-differencing. Differencing is a standard data process strategy in GNSS data process to mitigate (or cancel out) the various errors (e.g. signal generation/emission, signal propagation, signal transmission and signal reception) inherited with the technology. Various analyses of the atmospheric profiles based on the single- and zero-differencing data processing strategies and using three months' data, are carried out to evaluate the quality of BDS GNOS RO data and the robustness/quality of the zero-differencing data processing method. By comparing with ECMWF model and co-located radiosonde data, the BDS GNOS atmospheric profiles derived are fairly consistent.
Data processing algorithms are introduced in a fairly detailed way. The analyses are described and presented in a logical and clear manner. The discussions are comprehensive albeit some further clarification is needed. The conclusions given from the analysis are sound and reflect the current state-of-the-art in the field.

Thank you.

Following are my other comments/suggestions for correction

1) FY-3C GNOS receivers can receive both the GPS and BDS signals for navigation and occultation modules, therefore GNOS provides a different way to validate its BDS RO data (i.e. based on the zero-difference processing and GPS RO retrievals). I wonder the reason why not to use the GPS GNOS RO retrievals to validate BDS's counterparts?

We agree that comparing with the GNOS GPS RO retrievals to validate BDS's counterparts is a good idea and a potential way to do the FY-3C GNOS RO data evaluation. However, the radiosonde observations and the ECMWF analysis data are reliable GNOS-independent data, which have previously been used as reference data to also validate GPS RO retrievals. Therefore, for this initial GNOS BDS evaluation we selected the radiosonde and ECMWF data as preferred source to use as reference to validate the BDS RO data. Nevertheless, since we could achieve a limited collocation ensemble of BDS RO and GPS RO, we included one BDS vs. GPS intercomparison figure now in section 3.2., which shows reasonably high consistency. Of course, further improvements and a detailed intercomparison analysis of the GPS and BDS RO data is a very interesting study, and we plan to do it by an extra paper.

2) The current coverage of Beidou is regional. It would be great if the authors can comment over the issue of limited coverage of the Beidou system and how it affects the ROE occurrence?

Thank you for pointing to this; we think, though, that in the view of the focus of this paper (an initial validation of the BDS RO profiles) we have commented on the current limitations of the BDS MEO, IGSO, and GEO subsystems in adequate length. We did so in the introduction, in section 3 where we also visualize the RO events occurrence in terms of the geographic coverage situation (Fig. 5), etc.

3)

- Technical Corrections - Define the acronym for GRAS, GEO, IGSO and etc. when they appear in the first place in the text and use the acronyms thereafter.

Ok, done.

- Page 3, lines 13-14: the word "satellites" is repeated.

Ok, corrected.

- Page 13, line 10: It looks like you might be missing a reference here.

Ok, a typo was left, corrected.

- Page 16, lines 4-5: Should be Allan deviation (ADEV), not Allen variance.

Ok, corrected.

- Be careful with some reference formats and typos.

Ok, looked again over the texts and further polished reference formats and typos.

- be careful in using the differential technique, you need to be consistent to use differencing or differenced or difference. They do have minor differences. The "single-different" in figure 5 (a)/(b) is NOT right.

Ok, corrected.

- the title of the paper looks awkward and it needs to change "processing" and "data" need to be "data processing"

Thank you, we carefully considered and tried this, but then preferred to keep the current formulation (expresses best in our view the aspect that we focus on the new BeiDou radio occultation data and that the key processing focus is excess phase processing). We made a little simplification, though, in leaving out the term "System" from the title, since "BeiDou radio occultation data" instead of "BeiDou System…" is sufficient in the title.

- GNSS is commonly referred to The Global Navigation Satellite Systems (plural!!!)

Yes, we agree this is done in particular if the plurality of the different constellations (in particular GPS, Glonass, BDS, Galileo) is emphasized. Since we use it as a generic term (collectively for the constellations), however, we generally prefer to follow the usual notation of using the term Global Navigation Satellite System as the name of the overall system.

- the language usage needs to be sharpened and grammatical problems are spotted.

Ok, as mentioned above, we rechecked all texts and the language usage has been improved.

- "sub-global" needs to be replaced as "regional"

Ok, done.

<u>Response to Anonymous Referee #4's comments</u>

General comments:

The paper describes the evaluation of zero-difference processing vs. single-difference processing of BeiDou System (BDS) radio occultation (RO) data collected by the Chinese GNOS instrument on board the FY-C3 satellite.

Although this is not the first paper describing GNOS BDS retrievals, it is the first paper describing the zero- and single-differencing methods in that context, and comparing results using either method. For that reason it should be published in AMT. There are, however, a number of issues that needs to be addressed in a revised version.

The single- and zero-differencing methods are outlined and their application seems sound, although not all relativistic corrections seem to be adequately described. This, together with small unexpected differences in the results, gives me a grain of uncertainty as to whether the relativistic effects and clock offsets are correctly removed. I elaborate on this in one of the specific comments below.

Thank you.

Comparisons of derived bending angle and refractivity to reference profiles from ECMWF analyses are encouraging, although I do not think the results presented show that GNOS BDS RO data are of such high quality as claimed in the text. The authors mention (top of page 11) that part of the bias in their results could be from differences in vertical geo-location of GNOS and reference profiles (which are from ECMWF analyses and radiosondes). I'm not sure that such differences could give rise to the biases that are shown, but if so, such systematic difference should be better understood in the presented data set and possibly corrected. I am not aware of bias problems in the data evaluation of GPS RO data from other sources, e.g., COSMIC/CDAAC or Metop/EUMETSAT. In my comments to the results in Fig. 6 and 7 below, I point to a few other issues that are not mentioned in the text, but which should at least be discussed if improvement of the results in a revised manuscript is not possible.

If improvement is not possible, then some of the statements in the paper should be toned down, e.g., in the abstract where it says that "The statistical evaluation against these reference data shows that the results from single- and zero-difference processing are consistent in both bias and standard deviation, clearly demonstrating the feasibility of zero-differencing for GNOS BDS RO observations.", or at the end of the abstract where it says "The validation results establish that GNOS can provide, on top of GPS RO profiles, accurate and precise BDS RO profiles both from single- and zero-difference processing." Although the GNOS BDS RO data might be of a very high quality comparable to that of GPS RO data, such claims are not fully supported by the results in this paper.

Thank you for these frank yet constructive comments. We agree that this paper is just an initial study to evaluate and show what we found to be a quite good quality already of the new GNOS BDS RO data. But of course, it clearly has further improvement potential from more rigorous future analysis, and we plan to do this by follow-on work. We therefore took your *suggestions serious, related to the scope and limitations of results of this initial paper, and carefully considered to tone down some statements in the paper; and we did so for several statements. For example, in the abstract we now say "are reasonably consistent" (instead of "are consistent") and "the validation results indicate" (instead of "the validation results establish"), etc.*

One thing that could give more confidence in the single- and zero-differencing results would be to show cases of ionospheric corrected excess phases at very high altitudes. Although the ionospheric correction in the processing is done at the bending angle level (at common impact parameters of B1 and B2 bending angles), excess phase data corrected at the same times could be shown for cases where the ionospheric residual is small (this could be based on the difference between B1 and B2 excess phases, choosing only cases where such difference/variation is small). If such cases, at altitudes above _100 km, show virtually no slope (giving confidence that the relativistic effects and clock offsets are correctly removed), and only noise at the level indicated in Fig. 3, then that would give added confidence in the quality of the data. A few examples together with statistical evidence that ionospheric corrected excess phases at high altitudes are virtually flat compared to the random noise, would make a very good case. Unfortunately, there is no method description of the derivation of bending angle and refractivity. Could such description be added (possibly just with reference to previous works)?
We agree it is basically a very good suggestion to look into such ionosphere-corrected excess phases at high altitudes, complementary to the current upper troposphere/lower stratosphere (UTLS) validation and with more rigor. In this initial study on GNOS BDS RO evaluation we preferred to focus on UTLS validation against GNOS-independent reference data, however, as we started to do in previous papers (e.g., Liao et al. AMT 2016) for GNOS GPS RO evaluation. As noted in the first response above, we agree that this paper is an initial step only and that more rigorous inspection of small residual errors, of different possible sources within the orbit determination and excess phase processing, are needed and will be done by us in follow-on work.
For the retrieval of bending angle and refractivity profiles from the excess phase data, we used the ROPP software (available from the European ROM SAF consortium); we added a clarifying sentence to this end in section 3.2.

A few additional questions comes to mind: Are there both setting and rising occultations in the statistics, and how many of each? How far down is the B2 signal typically tracked in rising and setting? How far up are the signals typically tracked? Are extrapolation of B1-B2 performed in the troposphere to extend profiles down to where B1 is tracked (if it is tracked lower than B2)?
Response: "Are there both setting and rising occultations in the statistics, and how many of each?" *Yes, the numbers of rising and setting are around half of the total number in Fig.1b, i.e., the contribution of setting and rising events to the total number is about the same.*
"How far down is the B2 signal typically tracked in rising and setting? How far up are the signals typically tracked?" *the B2 signal typically could track down to about 5 km, near half of them could track down to about 3 km, few of them could track down to 2 km or more.*

"Are extrapolation of B1-B2 performed in the troposphere to extend profiles down to where B1 is tracked (if it is tracked lower than B2)?" *We did not use the B1-B2 extrapolation in the BDS processing so far, but we consider to do it in future and will evaluate this further.*

Below I give specific comments and technical corrections with <page>/<line> referring to the pdf copy of the manuscript. In some places I give suggestions for improved language that could easy the readability, but not in all places where such improvement could be warranted. Suggested words are in square brackets. I kindly urge the authors to run the manuscript by a person with excellent skills in the English language.

Specific comments and Technical corrections:

1/3: Consider a small change to the title: "... data [from] the FY-3C GNOS mission"
Ok, done.

1/22: "[The] GNOS ..."
Ok, done.

1/26: "... on [the] FY-3C GNOS, [and] thus ..."
Ok, done.

2/12: Skip "as small as".
Ok, done.

2/13-14: Bad syntax: "including for the GEO, IGSO, and MEO subsets.". Could be skipped here, since you already indicated earlier in the abstract that the data are from these three sub-systems.
Ok, done.

2/14-15: "as may be expected from its lower vulnerability to noise." could also be skipped here.
Thank you for the suggestion, we carefully considered it but we then preferred to keep this sentence here, to explain the potential reason.

2/17: "... satellites [can] thus provide..."
Ok, done.

2/24-26: Move "Earth's" to before "atmospheric parameters...".
Ok, done.

3/9: "LEO" is not previously defined.
Ok, done.

3/20-23: I suggest reformulation, e.g.: "One of these LEO missions is the FengYun 3

series C satellite (FY-3C), carrying China's first GNSS Occultation Sounder (GNOS) (Liao et al., 2016). FY-3C was successfully launched on 23 September 2013."
Thank you, done.

3/28: I suggest reformulation, e.g.: "... satellites, the next being FY-3D, scheduled for launch in 2017, will also carry GNOS instruments, similar to ..."
Thank you, done.

4/1-3: Please reformulate. Are the antennas considered part of the instrument (line 1) or are they used by the instrument (lines 2-3)?
Yes, all these antennas are used by the instrument.

4/4: "... in [the] GNOS design.".
Ok, done.

4/5: "... from Earth's surface ..."
Ok, done.

4/13: Replace "it" with "the single-difference method".
Ok, done.

4/15: "... [the] single-difference ..."
Ok, done.

4/15-16: Redundant information (and bad syntax) that could be skipped: "during the GPS clock offset estimation process."
Ok, done.

4/17: "... needs no ground station data, [the] processing is simpler".
Ok, done.

4/24: "...requires that the LEO receiver [is equipped with] an ...".
Ok, done.

4/26: "... is [equipped with] such ...".
Ok, done.

4/31: "... received [the signals from five] geostationary ... (MEO) orbit satellites.".
Ok, done.

Section 1: Perhaps you could mention the B1 and B2 frequencies somewhere in the introduction. Section 1: Perhaps you could mention the different semi major axes and inclination of the GEO, IGSO, and MEO sub-systems somewhere in the introduction.
Ok, done.

5/23: "Recently, [because of] its higher complexity ...".
Ok, done.

6/1: "The inputs to [the processing] ...".
Ok, done.

6/20: "... for [the] receiver clock and [the] GNSS satellite clock ...".
Ok, done.

6/9-11: I do not understand this sentence: "Specifically, in this study, we use the BDS satellite data as orbital data inputs and outputs, while time-wise also using GPS time for the processing of the BDS data." Please clarify.
It means, the GPS time is used for time-tagging also of the BDS observations, while the transmitter orbit data are of course the BDS data. We have clarified the sentence in the text.

6/13: "(in units of [length]) at [carrier signal] i". (also in first line of page 7)
Ok, done.

6/16: Is there a reference for eq. (1)?
Ok, done; we included Schreiner et al. (2010) now:
Schreiner, W., Rocken, C., Sokolovskiy, S., and Hunt, D.: Quality assessment of COSMIC/FORMOSAT-3 GPS radio occultation data derived from single- and double-difference atmospheric excess phase processing. GPS Solut., 14, 13-22, doi:10.1007/s10291-009-0132-5, 2010.

6/17: Skip "(m/s)"
Ok, done.

7/4: Superscript on last term in eq. (2) should be "c".
Ok, done.

7/10: Superscript "a" should be "b" on the left-hand side of eq. (3).
Ok, done.

7/12: Shouldn't it be capital letters "B or C" here?
Thank you, we chose to revise the labels 'A B C' to 'a b c' in Figure 1, to be more easily consistent everywhere.

7/17: Please provide a reference for eq. (4). You say that this is a "periodic relativistic effect", but does not mention the main part of the relativistic correction, and it is therefore unclear if you make all the necessary corrections. If I understand relativistic effects in the GPS correctly, then eq. (4) is a residual that comes about because the GPS transmitters have their clocks

adjusted prior to launch, such that the GPS clocks in orbit beat at the same rate as a clock on the Earth (Ashby, Relativity in the Global Positioning System, Living Rev. Relativity, 6, (2003), 1, http://www.livingreviews.org/lrr-2003-1). However, part of that adjustment of the transmitter clock results in an additional frequency shift in ECI that must be taken into account in the zero-differencing (it cancel in the single-differencing). The shift is proportional to the effective gravitational potential at the surface of the rotating Earth, and is actually larger then the relativistic effect in orbit that would have been without this clock adjustment. See, e.g., eq. (46) in Ashby (2003). You should make clear how you make this additional correction. Ashby describes the relativistic effects in the GPS. Are clocks in the BDS similarly adjusted before launch? If so, it would be interesting if you could give the different values of the frequency adjustments in the BDS subsets (GEO, IGSO, and MEO). Also, eq. (4) is relevant for GNSS clocks (as you write), but what about the relativistic effects of the FY-3C satellite clock? They do not seem to be described? Nor is it mentioned how they are estimated in the zero-differencing. Again, eq. (46) in Ashby (2003) could be of help here. In any case, you should make clear how you estimate all the main relativistic effects and clock offsets (please also make clear whether you consider the correction for the transmitter clock adjustment part of the clock offset or part of the relativistic effects).
Ok, done as good as we could for now. The reference for Eq. (4) is as well: Schreiner, W., Rocken, C., Sokolovskiy, S., and Hunt, D.: Quality assessment of COSMIC/FORMOSAT-3 GPS radio occultation data derived from single- and double-difference atmospheric excess phase processing. GPS Solut., 14, 13-22, doi:10.1007/s10291-009-0132-5, 2010.
And yes, the clocks of BDS are similarly adjusted prior to launch as for GPS. So the same equations as for GPS can be used for BDS data processing. In terms of the values of frequency adjustments, they depend on the orbit altitudes, BDS MEO satellite are set closely similar as GPS satellite; and the BDS GEO and IGSO satellite clocks are set to slightly different values. Currently in our data processing, we did not consider the LEO satellite relativistic effects but investigate in this direction for future updates.
We have included this type of explanations in the text below Eq. (4) now.

7/18: Shouldn't there be bars above r and v here?
Ok, done.

7/18: Shouldn't it be "GNSS" instead of "GPS"?
Ok, done.

7/20: Please provide a reference for eq. (5).
Ok done. It is again Schreiner et al (2010):
Schreiner, W., Rocken, C., Sokolovskiy, S., and Hunt, D.: Quality assessment of COSMIC/FORMOSAT-3 GPS radio occultation data derived from single- and double-difference atmospheric excess phase processing. GPS Solut., 14, 13-22, doi:10.1007/s10291-009-0132-5, 2010.

7/20: Subscript "r" should be "a" five places in eq. (5).
Ok, done.

8/2: I think eq. (6) needs to be multiplied by the i'th wavelength to be consistent with the terms in eq. (1) and (2).
Ok, done.

8/3: In eq. (4) bars were used to indicate vectors, so it is unfortunate here to distinguish the two effective dipole vectors by a bar on one, but not the other. I suggest to use another distinction and consistently use bars to indicate vectors.
Ok, done. We have used the bold italic letters as vectors.

Section 2.1: Generally, It would make good sense to mention the order of magnitude of different corrections and their relative importance.
Now that we have the references included we considered it makes the text less concise to read if we include also this. Also for the purpose of this paper it is an introductory description to the excess phase equations; in the follow-on study looking in detail into the improvement of remaining small residual errors in the excess phase processing we would of course intend to describe these aspects in more detail.

8/6: I suggest skipping "adopt".
Ok, done.

8/10: I suggest to remove "employing Eq. (2),".
Ok, done.

8/14-16: Some of the "a" and "c" subscripts and superscripts on the right-hand sides of eq. (7) and (8) should be interchanged.
Ok, done.

8/14-16: I suggest the use of different symbols in eq. (7) and (8) (and similar in eq. 9) for the phases on the right-hand side, since these are corrected for the effects mentioned in the first paragraph of this section. Perhaps you could simply use a tilde to indicate that they are not strictly the same as the ones in eq. (1) and (2), and at the end of the first paragraph in section 2.2 (line 9) you could write something like: "In the following we refer to these as <symbol_ab> and <symbol_ac>, respectively."
Ok, done.

8/18: I suggest replacing ". c1 and c2 are just" with "are".
Ok, done.

9/18: You could say "mentioned" instead of "aforementioned".
Ok, done.

9/21: Could the occulting and reference satellites be from two different sub-systems, e.g., a MEO as reference for an occulting GEO?

Yes.

10/1-2: It is not clear how you calculate the "carrier phase observation error standard deviation" shown in Fig. 3. Are you applying a high-pass filter? With what band-width?
Yes, in the processing a high-pass filter has been used and the band-width chosen was seven seconds. Please refer to: Oliver Montenbruck, Yago Andres, Heike Bock, et al. (2008); Tracking and orbit determination performance of the GRAS instrument on MetOp-A. GPS Solut., 289-299.

11/24 (and other places): You could use the word "difference" instead of "error".
We considered this, but given the rest of the relevant notation as used in this paper, we preferred to keep the current terminology also here.

11/25: Use a mathematical symbol for bending angle in eq. (11) (BA is an abbreviation, not a symbol).
Ok, done, we use the greek symbol Alpha now, which is often used for bending angle in the RO community.

11/28: You could here introduce the use of "Bias" and "StdDev" as they are used later in the text: "... estimates of biases (Bias) and standard deviations (StdDev) are illustrated ...".
Ok, done.

12/27-28: I do not understand the sentence in parenthesis: "though more standard deviation suppression might be expected from avoiding the reference link computation". It is not clear what "standard deviation suppression" mean, and I'm not sure if this statement is different from what you just said in the sentence before? Using the word "though" indicates that it is contradicting what you said before. Please clarify.
Ok, clarified.

12/28: Schreiner et al. 2009 is not in the reference list. Should perhaps be 2010.
Ok, done.

13/3: "Scherllin" instead of "Scherrlin".
Ok, done.

13/10: Empty parenthesis. Perhaps a reference is missing.
Ok, a typo was left, corrected.

13/11-12: Is it really the first time that RO retrievals from other than the BDS MEO is demonstrated? Liao et al. (2016) also describes the GNOS-BDS occultation coverage using BDS GEO and IGSO, and I could not find any indication in their paper that the statistics they show is only from MEO occultations. If it is the first time, then you should here make clear that the results in Liao et al. (2016) did not include GEO and IGSO occultations.

Ok, revised.

14/3: You say that GNOS BDS retrievals are comparable to GPS retrievals, but you have not really shown that here. Either you should show comparisons to GPS retrievals, or you need to support such statements with citations to previous works.

We agree that comparing with the GNOS GPS RO retrievals to validate BDS RO retrievals is a good idea and a potential complementary way to do the FY-3C GNOS RO data evaluation. However, the radiosonde observations and the ECMWF analysis data are reliable GNOS-independent data, which have previously been used as reference data to also validate GPS RO retrievals. Therefore, for this initial GNOS BDS evaluation we selected the radiosonde and ECMWF data as preferred source to use as reference to validate the BDS RO. Nevertheless, since we could achieve a limited collocation ensemble of BDS RO and GPS RO, we included one BDS vs. GPS intercomparison figure now (in section 3.2.), which shows reasonably high consistency. Of course, further improvements and a detailed intercomparison analysis of the GPS and BDS RO data is a very worthwhile next study as well, and we plan to do it by an extra paper.

14/5: "... not [only] on MEO satellites but [also] on GEO and IGSO satellites.".

Ok, done.

14/26: You say that "Single-differencing does not need to correct the receiver clock offset". I know what you mean, but it is not strictly correct. The receiver clock offset is removed because it cancel in the single-differencing. Please reformulate.

Thank you, done.

15/2-4: You say that in the zero-differencing there can be some residual errors after the clock offset correction, but you have not shown that anywhere. Can you give examples of such residuals?

After the LEO clock correction in zero-difference, the LEO clock left a residual errors, which could be estimated by stability of the LEO clock. We can use the Allan deviation to describe it; for more information you can refer to Figure 10 in

"Cai Y, Bai W, Wang X, et al. In-Orbit Performance of GNOS on-board FY3-C and the Enhancements for FY3-D Satellite. Advances in Space Research, 2017."

16/4: It should be "Allan", not "Allen".

Ok, done.

16/5: Please reformulate the statement on the Allan variance (or deviation) here. It is correctly formulated in the abstract. The unit is not second.

Ok, done.

16/10-12: The last paragraph should be reformulated or removed. It is unclear what "in this context of the leading instruments" means.

Ok, done.

Results shown in Figure 6:

1) StdDev: I would have expected visible differences between single- and zerodifferencing to be only at high altitudes/impact heights. However, even below 10 km it seems that the StdDevs are significantly different, with the zero-differencing results generally having the larger StdDev. How can that be explained? From the legend it appears that it is exactly the same number of occultations involved (and I assume therefore that it is the same occultations). Also, it seems that the StdDev starts increasing already at 20-25 km. I would have expected the increase to start a bit higher when I compare with GPS RO statistics from other sources.

For the StdDev profile differences below about 10 km and above about 20-25 km, the reasons are likely somewhat complicated (several possible sources in the excess phase processing, also BDS ephemeris, esp. for GEO) and we are analyzing this type of differences in follow-on work to this initial study. We have included a clarifying sentence explicitly pointing to this.

On the "same number of occultations", yes, both ZD and SD involve the same RO events.

2) Bias: The differences in bias between single- and zero-differencing are similar below 20 km, and the somewhat larger negative bias for GEO can probably be explained by the fact that all the GEO occultations are at very high altitudes (and for some reason that gives a larger negative bias when compared to ECMWF). However, above 20 km, the biases for the three subsystems (MEO, IGSO, GEO) are diverging more for the zero-differencing results, and in particular the bias for the GEO occultations becomes more negative than it is for single-differencing. Why?

These issues needs to be discussed in the text.

See the previous response above, which in general also holds here; more detailed follow-on work will clarify the more subtle differences. We have include an additional sentence related to the specifics of the GEO RO events now as well, pointing to the fact that the GEO orbit determination is the most challenging from all BDS and that the GEO RO events are restricted to high latitudes only (as visible in Fig. 5), i.e., a potential regional selection effect.

Results shown in Figure 7:

The same comments as above applies here, but additionally, it is very strange to see the bias for the GEO occultations for single-diffencing at high altitudes being more positive than the others. This is inconsistent with the biases in the bending angle. It is critically important to understand this, since you are trying to make the point that zero-differencing has lower StdDev than single-differencing, but it is difficult to have confidence in the results if there are such inconsistencies in the biases.

On top of what is said above related to the bending angle Figure, we also included a sentence here for refractivity, pointing to the follow-on work for detailed error analysis and to the specifics of the GEO results.

Figure 8 axes labels: I suggest to redo this figure with labels as in Figure 7 ("R%" does not make sense; "geop" should be "Geopotential height").

Ok, done.

Evaluation of atmospheric profiles derived from single- and zero-difference excess phase processing of BeiDou radio occultation data from the FY-3C GNOS mission

Weihua Bai[1,2,4], Congliang Liu[1,4], Xiangguang Meng[1,4], Yueqiang Sun[1,2,4], Gottfried Kirchengast[3,4,1], Qifei Du[1,4], Xianyi Wang[1,4], Guanglin Yang[5], Mi Liao[5] , Zhongdong Yang[5], Danyang Zhao[1,4], Junming Xia[1,4], Yuerong Cai[1,4], Lijun Liu[1,4], and Dongwei Wang[1,4]

[1] National Space Science Center, Chinese Academy of Sciences (NSSC/CAS) and Beijing Key Laboratory of Space Environment Exploration, Beijing, China
[2] School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing, China
[3] Wegener Center for Climate and Global Change (WEGC) and Institute for Geophysics, Astrophysics, and Meteorology/Institute of Physics, University of Graz, Graz, Austria
[4] Joint Laboratory on Occultations for Atmosphere and Climate (JLOAC) of NSSC/CAS, Beijing, China, and University of Graz, Austria
[5] National Satellite Meteorological Center, Chinese Meteorological Agency, Beijing, China
Correspondence to: Liu Congliang (Email:liucongliang1985@gmail.com), Xiangguang Meng (xgmeng@nssc.ac.cn)

Abstract

The Global Navigation Satellite System (GNSS) Occultation Sounder (GNOS) is one of the new generation payloads onboard the Chinese FengYun 3 (FY-3) series of operational meteorological satellites for sounding the Earth’s neutral atmosphere and ionosphere. The GNOS was designed for acquiring setting and rising radio occultation (RO) data by using GNSS signals from both the Chinese BeiDou System (BDS) and the U.S. Global Positioning System (GPS). An ultra-stable oscillator with 1-sec stability (Allan deviation) at the level of 10^{-12} was installed on the FY-3C GNOS, and thus both zero-difference and single-difference excess phase processing methods should be feasible for FY-3C GNOS observations. In this study we focus on evaluating zero-difference processing of BDS RO data vs. single-difference processing, in order to investigate the zero-difference feasibility for this new instrument, which after its launch in September 2013 started to use BDS signals from 5 geostationary orbit (GEO) satellites, 5 inclined geosynchronous orbit (IGSO) satellites and 4 medium earth orbit (MEO) satellites. We used a 3-month set of GNOS BDS RO data (October to December 2013) for the evaluation and compared atmospheric bending angle and refractivity profiles, derived from single- and zero-difference excess phase data, against co-located profiles from ECMWF (European Centre for Medium-Range Weather Forecasts) analyses. We also compared against co-located refractivity profiles from radiosondes. The statistical evaluation against these reference data shows that the results from

single- and zero-difference processing are reasonably consistent in both bias and standard deviation, clearly demonstrating the feasibility of zero-differencing (ZD) for GNOS BDS RO observations. The average bias (and standard deviation) of the bending angle and refractivity profiles were found to be about 0.05 % to 0.2 % (and 0.7 % to 1.6 %) over the upper troposphere and lower stratosphere. Zero-differencing was found to perform slightly better, as may be expected from its lower vulnerability to noise. The validation results indicate that GNOS can provide, on top of GPS RO profiles, accurate and precise BDS RO profiles both from single- and zero-difference processing. The GNOS observations by the series of FY-3 satellites are thus expected to provide important contributions to numerical weather prediction and global climate change analysis.
Keywords: radio occultation, FY-3 GNOS validation, BeiDou System (BDS), excess phase, single-differencing, zero-differencing

1 Introduction

The radio occultation (RO) technique (Melbourne et al., 1994; Ware et al., 1996) using signals from the Global Navigation Satellite System (GNSS), in particular from the Global Positioning System (GPS) so far, has been widely used to observe the Earth's atmospheric parameters (e.g., bending angle, refractivity, temperature, pressure, and water vapor) for applications such as numerical weather prediction (NWP) (e.g., Healy and Eyre, 2000; Kuo et al., 2000; Healy and Thepaut, 2006; Aparicio and Deblonde, 2008; Cucurull and Derber, 2008; Poli et al., 2008; Huang et al., 2010; Le Marshall et al., 2010; Harnisch et al., 2013) and global climate monitoring (GCM) (e.g., Steiner et al., 2001, 2009, 2011, 2013; Schmidt et al., 2005, 2008, 2010; Loescher and Kirchengast, 2008; Ho et al., 2009, 2012; Foelsche et al., 2011a; Lackner et al., 2011).

The RO concept was experimentally tested by the first experimental Global Positioning System/Meteorology (GPS/MET) mission launched in 1995 right after the full operational capacity of GPS was achieved (Ware et al., 1996; Kursinski et al., 1996; Kuo et al., 1998). GPS/MET has demonstrated the unique properties of the GPS RO technique, such as high vertical resolution, high accuracy, all-weather capability and global coverage (Ware et al., 1996; Gorbunov et al., 1996; Rocken et al., 1997; Leroy, 1997; Steiner et al., 1999).

The subsequent Low Earth Orbit (LEO) satellite missions such as the CHAllenging Minisatellite Payload (CHAMP) (Wickert et al., 2001, 2002), the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) (Anthes et al., 2000, 2008; Schreiner et al., 2007), the Gravity Recovery And Climate Experiment (GRACE) (Beyerle et al., 2005; Wickert et al., 2005), and the Meteorological Operational (MetOp) (Edwards and Pawlak, 2000; Luntama et al., 2008) satellites have further affirmed the long term stability and remarkable consistency (e.g., <0.2–0.5 K in temperature) of RO observations from different RO missions (Foelsche et al., 2009, 2011a).

The development of GNSS such as China's BeiDou Navigation Satellite System (BDS), Russia's GLObal NAvigation Satellite System (GLONASS), and the European Galileo system, has significantly enhanced the availability and capacity of the GPS-like satellites which will make RO even more attractive in the future. These new GNSS navigation satellites together with planned LEO missions will offer many more RO observations. One of these LEO missions is the FengYun 3 series C satellite (FY-3C), carrying China's first GNss Occultation Sounder (GNOS). FY-3C was successfully launched on 23 September 2013 (Bai et al., 2014; Liao et al., 2016).

FY-3C GNOS, developed by National Space Science Center/Chinese Academy of Sciences (NSSC/CAS), is the first BDS/GPS compatible sounder and combines a state-of-the-art RO receiver with an ultra-stable oscillator. The future satellites of the Chinese FY-3 series of operational meteorological satellites, the next being FY-3D, scheduled for launch in 2017, will also carry GNOS instruments, similar to the MetOp series of European satellites with its GNSS Receiver for Atmospheric Sounding (GRAS) instruments (Loiselet et al., 2000).

The GNOS instrument consists of three antennas, three radio frequency (RF) units and a data processor (Figure 1a), which uses high-dynamic, high-sensitivity signal acquisition and tracking techniques, in which the navigation antenna with stable phase center. Additionally, the different features of BDS and GPS signals have been taken into account in the GNOS design. The GNOS can observe the atmosphere and ionosphere and its detection height range is from Earth's surface to around 800 km altitude. So far, a 4-year dataset of FY-3 GNOS RO observations has been obtained. Figure 1b illustrates the number of both the GPS RO and BDS RO events processed over the three months from October to December 2013, which are used for the single- and zero-difference excess phase analysis in this paper.

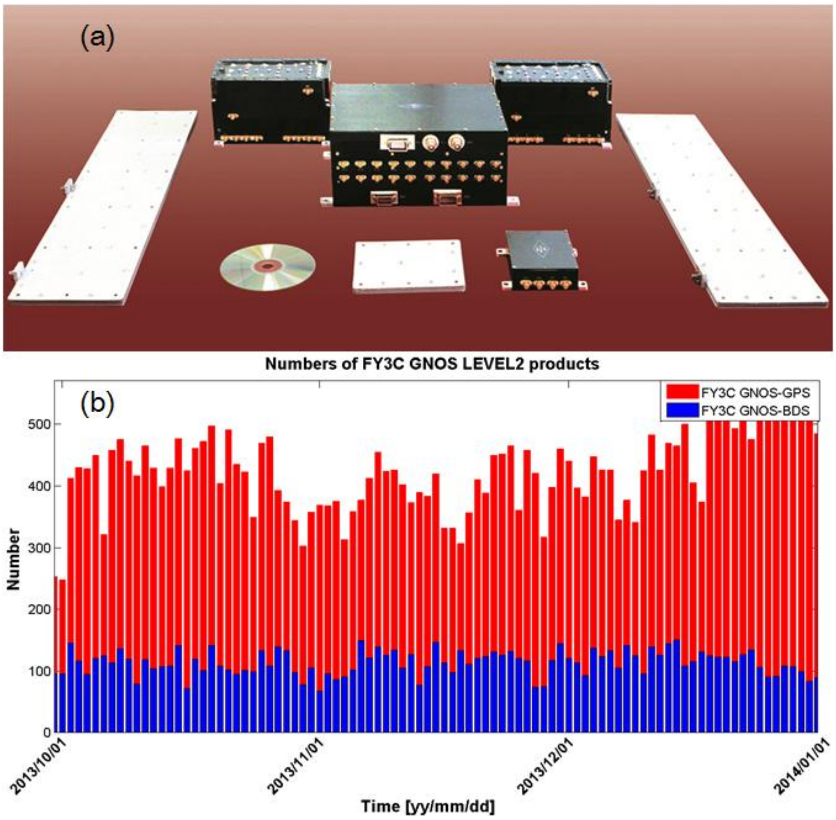

Figure 1. Components of the GNOS instrument (setting/rising occultation antenna and RF unit, left/right; navigation antenna and RF unit, middle in front; tracking and data processing unit, middle in back) **(a)**, and illustration of the daily number of high-quality FY-3C GNOS GPS and BDS RO events for October-December 2013 as used in this study **(b)**.

Regarding the excess phase processing, a single-difference method removes the LEO satellite clock offset by the difference between the GNSS occultation satellite and its GNSS reference satellite (Wickert et al., 2002). Comparing with the original double-difference method (Ware et al., 1996; Rocken et al., 1997), the single-difference method uses the solved GNSS satellite clock offset estimates instead of further differencing between the GNSS satellites and a GNSS ground station, hence the single-difference method can minimize the effects of ground data error sources (Hajj et al., 2002; Schreiner et al., 2010). Because single-differencing (SD) needs no ground station data, the processing is simpler and easier to realize. Therefore the single difference approach has become widely used in RO data processing after the switch-off of the GPS "selective availability" (SA) mode as of May 2000 (Hajj et al., 2002), which made GPS clock offset estimation sufficiently reliable.

Even more recently, zero-difference processing was started to be used (Beyerle et al. 2005; Wickert et al., 2005), which can compute excess phase data by applying prior estimated LEO and GNSS clock offsets without need of a reference satellite or ground station. However, it requires that the LEO receiver is equipped by an ultra-stable oscillator that, so far, was only available for the GRACE and MetOp missions (Beyerle et al. 2005; Luntama et al., 2008). The FY-3 GNOS instrument is equipped with such an ultra-stable oscillator as well.

BDS is China's global navigation satellite system designed to provide global coverage around 2020, with positioning, navigation, timing, and short-message communication service capabilities (Li, 2016). So far, BDS can provide good regional coverage in the Asia-Pacific area with an incomplete constellation, by using two L band frequencies, B1I = 1561.098 MHz (B1) and B2I = 1207.140 MHz (B2). For the time period of this study in fall 2013, the FY-3C GNOS received signals from five geostationary orbit (GEO) satellites (inclination 0°, mean altitude 35786 km), five inclined geosynchronous orbit (IGSO) satellites (inclination 55°, mean altitude 35786 km) and four medium earth orbit (MEO) satellites (inclination 55°, mean altitude 21528 km) to conduct the radio occultation measurements.

This still growing constellation also provides a practical motivation for zero-differencing (ZD) because not all of the FY-3C GNOS BDS RO events can be processed by single-differencing, since the incomplete BDS system cannot provide reference satellites for all RO events. On the other hand, the ultra-stable oscillator driving the GNOS receiver makes zero-differencing attractive to be potentially used as the method of choice for all BDS RO events. To investigate the feasibility of the zero-difference algorithm for BDS RO data processing, and to evaluate the quality of the retrieved RO data products, we therefore perform in this study a comparative analysis of zero- and single-difference processing for GNOS.

The paper is structured as follows. Section 2 provides a description of our single- and zero-difference excess phase processing. Section 3 presents the FY-3C GNOS datasets and the methods for the inter-comparison analysis. Section 4 presents the statistical analysis results for the various reference datasets. Finally, conclusions have been drawn in Section 5.

2 Calculation of the FY-3C GNOS excess phase profiles

Excess phase is a key variable during the radio occultation data processing and GNSS satellite and LEO satellite clock errors are main factors effecting the excess phase accuracy. As summarized above, these two clock error components can either be eliminated by double-differencing, or (for GPS after the SA mode has been deactivated) the GNSS clock errors are estimated and subtracted and so single-differencing can be applied, or (given an ultra-stable oscillator at the LEO) both clock errors are estimated and subtracted and so zero-differencing is possible. Recently, because of its higher complexity and degraded accuracy, double-differencing is rarely used. In this section we describe the single- and zero-difference procedures, which we used for the FY-3C GNOS excess phase processing.

2.1 Basic algorithm of the excess phase processing

The GNOS RO excess phase processing determines the total excess phase, which is caused by both the atmosphere and ionosphere, of the GPS L1, L2 and BDS B1, B2 signals as a function of coordinate (GPS) time in the Earth-Centered Inertial (ECI) True of Date (TOD) reference frame. The inputs to the processing are GPS, BDS and LEO satellite positions, velocities and clock offsets as a function of coordinate time, LEO satellite attitude information, carrier phase measurements, antenna phase center information, and Earth orientation information.

The outputs of this process include GPS time of the RO event observations, where we adopt the LEO's signal reception time, GPS L1, L2 and BDS B1, B2 total excess phases, position and velocity of the LEO satellite at signal reception time, and position and velocity of the GNSS satellite at signal transmission time. Hereafter, we will use the term GNSS to refer to GPS and BDS satellites, as well as use *L* to denote the excess phases not only for GPS signals but also for BDS signals. Specifically, in this study, we use the BDS satellite data as orbital data at transmitter side, while time-wise using the GPS time also for the processing of the BDS data. Figure 2 illustrates the geometrical basis of the differencing procedures as part of the excess phase processing.

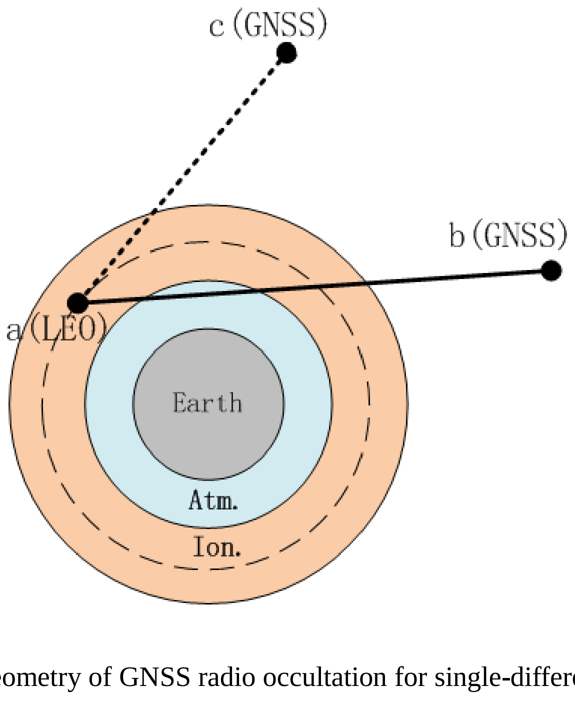

Figure 2. Schematic geometry of GNSS radio occultation for single-differencing (using link a-c in addition to link a-b) and zero-differencing (using link a-b only).

The observed carrier phase $L_{a,i}^{b}$ (in units of length) at carrier signal *i* between the LEO receiver satellite *a* and the occulting GNSS transmitter satellite *b*, as shown in Figure 2, is the essential raw observable which is modeled as (Schreiner et al., 2010)

$$
\begin{aligned}
&L_{a,i}^{b}(t_r) = \rho_a^b(t_r) + c(\delta t_a - \delta t_{a,rel}) - c(\delta t^b - \delta t_{rel}^b) + \delta\rho_{a,rel}^{b}(t_r) \\
&+ \Delta\phi_{a,i}^{b}(t_r) + \delta\rho_{a,ion,i}^{b}(t_r) + \delta\rho_{a,trop,i}^{b}(t_r) \ ,
\end{aligned}
\tag{1}
$$

where t_r is receive time, *c* speed of light in vacuum, ρ_a^b geometric range between *a* and *b* at receive time, δt_a, δt^b offsets between receive time and proper time and transmit time and proper time, respectively, $\delta t_{a,rel}$, δt_{rel}^b offsets between proper time and coordinate time due to special and general relativity for the receiver clock and the GNSS satellite clock, respectively, τ_a^b light travel time between receiver and transmitter in vacuum, $\delta\rho_{a,rel}^b$ gravitational delay between receiver and transmitter, $\Delta\phi_{a,i}^b$ phase wind-up correction at receive time, $\delta\rho_{a,ion,i}^b$ ionospheric excess phase between receiver and transmitter satellite, and $\delta\rho_{a,atm,i}^b$ neutral atmospheric excess phase between receiver and transmitter satellite. The ionospheric and neutral atmospheric components $\delta\rho_{a,atm,i}^b$ and $\delta\rho_{a,ion,i}^b$ jointly are the desired total excess phase to be determined based on Eq. (1).

Needed for single-difference processing only, the carrier phase observable $L_{a,i}^c$ at carrier signal *i* between LEO receiver *a* and reference GNSS satellite *c* is formally very similar to the one of the occultation link *a*-*b* and modeled as

$$
\begin{aligned}
&L_{a,i}^{c}(t_r) = \rho_a^c(t_r) + c(\delta t_a - \delta t_{a,rel}) - c(\delta t^c - \delta t_{rel}^c) + \delta\rho_{a,rel}^{c}(t_r) \\
&+ \Delta\phi_{a,i}^{c}(t_r) + \delta\rho_{a,ion,i}^{c}(t_r) \ ,
\end{aligned}
\tag{2}
$$

where the superscript *c* denotes the reference GNSS satellite and the meaning of the terms is otherwise as for Eq. (1). Since the reference link *a*-*c* crosses only (a part of) the ionosphere, the atmospheric excess phase term does not appear in Eq. (2).

The geometric range $\rho_a^{b,c}$, of the occultation link a-b or the reference link *a*-*c*, can be computed by

$$
\rho_a^{b,c} = \sqrt{\left(X^{b,c} - X_a\right)^2 + \left(Y^{b,c} - Y_a\right)^2 + \left(Z^{b,c} - Z_a\right)^2} \ ,
\tag{3}
$$

where ($X_a \quad Y_a \quad Z_a$) denotes the coordinates of the LEO satellite (*a*) at receive time and ($X^{b,c}$ $Y^{b,c} \quad Z^{b,c}$) denotes the coordinates of the GNSS satellite *b* or *c* at transmit time.
The GNSS satellite orbits (positions and velocities) and the GNSS clock offset estimates $\delta t^{b,c}$ are provided by the International GNSS Service (IGS) and applied as needed (a transformation from the International-Terrestrial-Reference-Frame of IGS to our True-of-Date reference frame is performed). Using the orbit information, the periodic relativistic effect of the GNSS satellite clock $\delta t_{rel}^{b,c}$ can be modeled by (Schreiner et al., 2010)

$$\delta t_{rel}^{b,c} = -2\frac{\boldsymbol{r}^{b,c}\cdot\boldsymbol{v}^{b,c}}{c^2} \ , \tag{4}$$

where $\boldsymbol{r}^{b,c}$ and $\boldsymbol{v}^{b,c}$ are the GNSS satellite position and velocity vectors at signal transmit time. Similar to the GPS, BDS clocks include an intrinsic frequency adjustment (to effectively beat at the rate of clocks at the Earth's mean-sea-level surface) in order to reduce the relativistic effect on the observations (Ashby, 2003). Regarding the values of the frequency adjustment, they depend on the orbit altitudes, i.e., the adjustment for BDS MEO satellites (~21500 km altitude) is closely similar to GPS satellites (~20200 km) while the BDS IGSO and GEO satellites (~35800 km) receive slightly different values. In our processing we do not (yet) account for the small relativistic effects on the LEO (GNOS) clocks but investigate towards potentially including also these effects in future.

The gravitational delay $\delta\rho_{a,rel}^{b,c}$ is modeled by (Schreiner et al., 2010)

$$\delta\rho_{a,rel}^{b,c} = \frac{2GM_E}{c^2}\ln\left(\frac{r^{b,c}+r_a+\rho_a^{b,c}}{r^{b,c}+r_a-\rho_a^{b,c}}\right) , \tag{5}$$

where G is Newton's gravitational constant, M_E is the Earth's mass, and $r^{b,c}$ and r_a are the transmitter and receiver radial positions at signal transmit and receive times, respectively.

The phase wind-up correction term $\Delta\phi_{a,i}^{b,c}$ can be modeled in the form

$$\Delta\phi_{a,i}^{b,c} = \lambda_i \cdot \mathrm{sign}\left(\boldsymbol{k}\cdot\left(\boldsymbol{D}\times D\right)\right)\cdot\cos^{-1}\left(D\cdot\boldsymbol{D}/\left(\left|D\right|\cdot\left|\boldsymbol{D}\right|\right)\right) , \tag{6}$$

where λ_i is the wavelength of carrier signal *i*, $\boldsymbol{k}$ is the unit vector from transmitter to receiver and D and $\boldsymbol{D}$ are so-called effective dipole vectors; for details on this modeling see Kouba (2015).

2.2 Single-difference processing

In the single-difference processing we use Eq. (1) as the basic equation and Eq. (2) as the auxiliary equation. GNSS clock offsets are subtracted and Eqs. (3) to (6) are applied to model and subtract also the GNSS-related geometric and relativistic terms from the occultation and reference link so that only the excess phases and LEO clock offsets remain.

Next, the excess phase of the reference link (which is only an ionospheric excess phase $\delta\rho_{a,ion,i}^{c}$) can be effectively eliminated by the classical dual-frequency ionospheric correction of L1 and L2 phases (e.g., Ware et al. 1996). That is, an ionosphere-corrected phase $L_{a,3}^c$ can be calculated for the reference link by what is the tilde on the symbols

$$L_{a,3}^c = L_{a,1}^c(t_r) + c_2\left\langle L_{a,1}^c(t_r) - L_{a,2}^c(t_r)\right\rangle$$

(7)

or

$$L_{a,3}^{c} = L_{a,2}^{c}(t_r) + c_1 \left\langle L_{a,1}^{c}(t_r) - L_{a,2}^{c}(t_r) \right\rangle \ ,$$

(8)

where $\langle \cdot \rangle$ denotes moving-average smoothing (over 2 seconds) and where $c_1 = f_1^2 / \left(f_1^2 - f_2^2 \right)$ and $c_2 = f_2^2 / \left(f_1^2 - f_2^2 \right)$ are just constants in which f_1 and f_2 are the frequencies of the L1 and L2 signals, respectively. In our processing we chose to employ Eq. (7) for the $L_{a,3}^{c}$ calculation.

Finally, the effects of the receiver clock, $c\left(\delta t_a - \delta t_{a,rel}\right)$, are eliminated by single-differencing (SD), that is by the subtraction of the reference-link phase $L_{a,3}^{c}$ from the occultation-link phases $L_{a,i}^{b}$, so that we obtain the desired SD-based total excess phase $\Delta L_{a,i}^{SD}$,

$$\Delta L_{a,i}^{SD}(t_r) = L_{a,i}^{b}(t_r) - L_{a,3}^{c}(t_r) = \delta\rho_{a,ion,i}^{b}\left(t_r\right) + \delta\rho_{a,atm,i}^{b}\left(t_r\right) \ . \qquad (9)$$

2.3 Zero-difference processing

The single-difference approach has some advantages as compared to double-difference, as noted in the introduction above, and has therefore been widely used in GPS RO data processing. However, it is difficult to find a suitable reference satellite for each RO event to calculate the excess phase using single-difference when the GNSS space segment is still an incomplete constellation, as with the current BDS.

Zero-differencing also will likely produce lower-noise excess phase data than single-differencing, from applying the estimated LEO clock offsets and avoiding the use of a reference link (being an additional error source). It can be employed if the LEO receiver is equipped with an ultra-stable oscillator such as in case of the GNOS instrument.

In the zero-differencing (ZD) approach we just employ Eq. (1) directly and model and subtract all relevant terms as summarized in subsection 2.1 above, including the GNSS and LEO clock offsets, so that we obtain the desired ZD-based total excess phase $\Delta L_{a,i}^{ZD}$,

$$\Delta L_{a,i}^{ZD}(t_r) = \delta\rho_{a,ion,i}^{b}\left(t_r\right) + \delta\rho_{a,trop,i}^{b}\left(t_r\right) = \\ L_{a,i}^{b}\left(t_r\right) - \left(\rho_a^b\left(t_r\right) + c\left(\delta t_a - \delta t_{a,rel}\right) - c\left(\delta t^b - \delta t_{rel}^b\right) + \delta\rho_{a,rel}^{b}\left(t_r\right) + \Delta\phi_{a,i}^{b}\left(t_r\right)\right) \ . \qquad (10)$$

3 Differencing and analysis methods for the GNOS BDS RO data

3.1 Necessity of zero-differencing for GNOS BDS RO data

As mentioned, the single-difference approach involves a GNSS reference satellite, which should have high signal to noise ratio (SNR) and high phase measurement accuracy. In order to use that specific reference satellite that most likely has the best signal quality and lowest ionospheric influence, our FY-3C GNOS receiver software chooses the GNSS satellite with highest elevation angle seen by the navigation (zenith) antenna as the reference satellite. For reasons of robustness and for ensuring best consistency, we so far only use BDS reference satellites for BDS occultations (likewise GPS reference satellites only for GPS occultations).

The largest gain and half-power beam width of GNOS's POD antenna is 5 dB and 40 degree, respectively, and the normal vector of the antenna plane points to the zenith, hence the antenna gain increases with increasing elevation angle. Therefore, ignoring the multi-path effect, the positioning channel carrier phase error increases with decreasing elevation and, ultimately, the satellite tracking will lose the lock when the elevation angle becomes very small.

Figure 3 illustrates the GNOS in-orbit testing results of the BDS B1 and B2 carrier phase observation error standard deviation, as a function of elevation angle. As can be clearly seen, both the B1 and B2 carrier phase measurement errors decrease with increasing elevation angle. At elevation angles larger than 10 deg, the B1 and B2 carrier phase errors are less than 2.2mm. Therefore, currently we select the reference satellite for the single-difference method from those satellites whose elevation angle is at least larger than 10 deg.

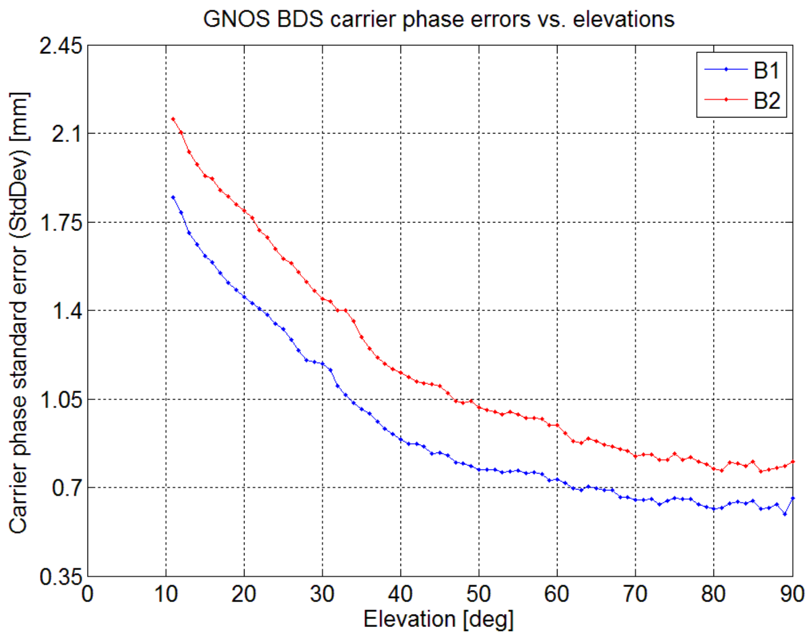

Figure 3. Statistics of FY-3C GNOS BDS carrier phase standard deviations (blue, B1 signal carrier phase; red, B2 signal carrier phase) as function of elevation angle, calculated by using positioning channel measurements.

Applying this 10-deg elevation threshold criterion, we counted the numbers of GNOS BDS RO events with and without reference satellites. In this statistical analysis all the GNOS BDS RO events that occurred from 1 Oct 2013 to 31 Dec 2013 were included. Figure 4 shows that during these 3 months there were 13564 GNOS BDS RO events in total, of which about 16% had a maximum elevation angle of possible reference satellites below 0 deg, and a total of 20% had their reference satellites below 10 deg. In practice, less than 10 deg means that the reference satellites' tracking accuracy is considered not sufficient for the single-differencing. Therefore, these 20% of BDS RO events can meaningfully be processed only by the zero-difference approach, since the still regional BDS system coverage cannot satisfy the 10-deg elevation threshold criterion for these events.

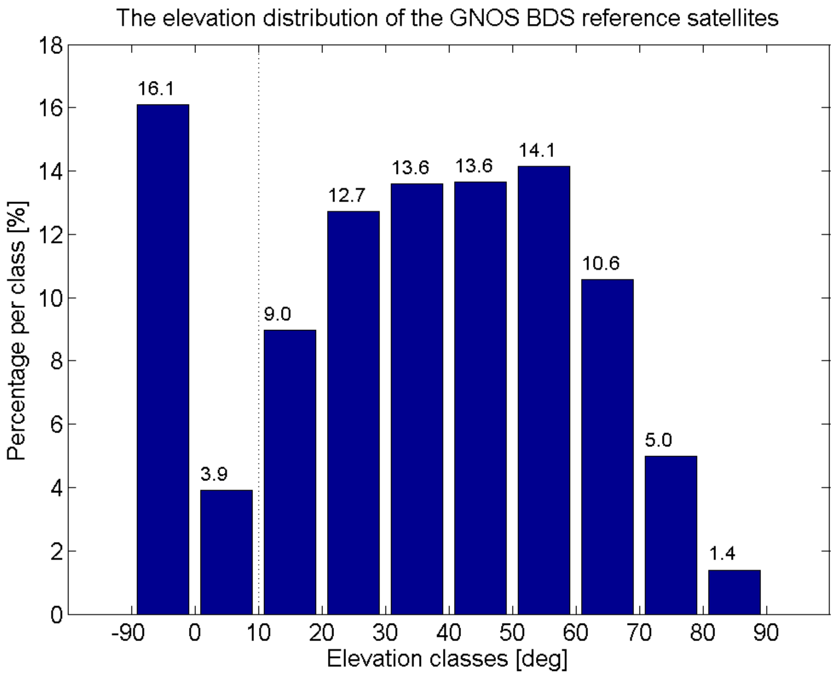

Figure 4. Histogram of the maximum elevation angle of the BDS reference satellites, with the statistics based on the 13564 BDS RO events that occurred over October-December 2013.

3.2 GNOS BDS RO data and statistical analysis method

To evaluate the performance of the zero- and single-difference methods, we have conducted a comparison analysis of the retrieved FY-3C GNOS BDS RO bending angle and refractivity data for the selected 92 days from 1 Oct 2013 to 31 Dec 2013, retrieved by either including the single-difference or zero-difference method in the excess phase processing.

In our data processing towards bending angle and refractivity, a quality control algorithm has been used (which for single-differencing reduced the profile dataset by about 2 %, for zero-differencing by less than 1 %). The processing statistics we obtain show that, after quality control, the number of RO events obtained by zero-differencing is higher by about 13 % than the one obtained by single-differencing, which we find is due to some ineffective reference BDS satellite links during the single-difference processing. The geographic and local time distribution of the RO events that also have proper BDS reference satellites for single-difference processing is shown in Figure 5.

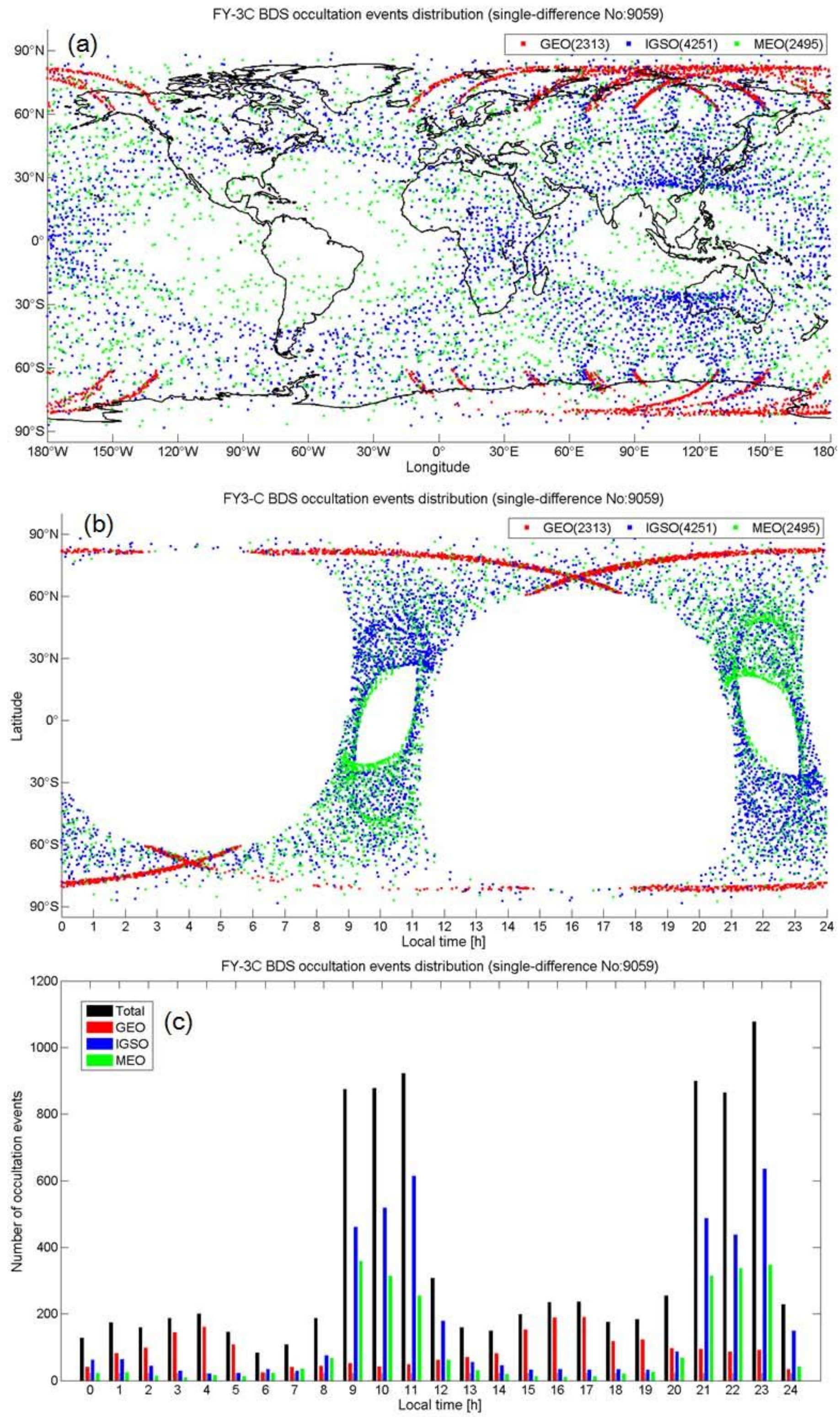

Figure 5. Geographical and local time distribution of the GNOS BDS RO events that have proper BDS reference satellites for single-difference processing (red, from the BDS-GEO satellites; blue, from BDS-IGSO; green, from BDS-MEO; numbers in parentheses denote the associated number of events during Oct-Dec 2013). Distributions are shown as function of latitude and longitude **(a)**, as function of local time and latitude **(b)**, and in histogram-style as function of local time (black

herein denotes from all BDS satellites) **(c)**.

Figure 5a shows that the geographic distribution of events well reflects the different BDS orbit types. BDS-GEO RO events mainly distribute in the southern and northern hemisphere high latitude zones along the longitude sector of the Chinese region. The number of BDS-IGSO RO events is highest, almost equal to the number of GEO and MEO RO events together. The BDS-IGSO RO event coverage forms a quasi-global "8" shape, with the larger oval over the American, Pacific, and Atlantic Ocean areas, and the somewhat smaller oval over southeast Asia, northwest Australia, Pacific, and Indian Ocean areas. Similar to the typical distribution of GPS RO events (e.g., Pirscher et al., 2007; Anthes et al., 2008), the BDS-MEO RO events show essentially global coverage, with more RO events in the middle and high latitude zones and less at low latitudes.

Figures 5b and 5c show the distribution of the RO events in a complementary way with focus on local time, again reflecting well the different BDS orbit types and their impact on RO event locations in space and time. It can be seen that the BDS-GEO RO events occur during all 24 hours of the day, while the BDS-IGSO and BDS-MEO RO events distribute mainly in the 9:00-11:00h and 21:00-23:00h local-time ranges (best seen in Fig. 5c). In particular at low and middle latitudes, equatorward of about 50° to 60°, no BDS RO events at all occur within about 00:00-08:00h and 12:00-20:00h local time (see Fig. 5b). This is due to the near-polar sun-synchronous orbit of the FY-3C meteorological satellite, similar to the European MetOp satellites as analyzed by Pirscher et al. (2007).

The distribution of the GNOS BDS RO events processed by using zero-differencing (not separately shown) is very similar to Figure 5, though with slightly more RO events (2623 BDS-GEO, 4820 BDS-IGSO, and 2863 BDS-MEO) that had passed the quality control.

Before the validation against the GNOS-independent reference data from the European Centre for Medium-range Weather Forecasting (ECMWF) and radiosondes, we furthermore did a cross-check of the quality of the BDS RO events based on a limited ensemble of co-located profiles we could achieve between GNOS BDS and GPS RO events.

Figure 6 shows the results of our inter-comparison of retrieved refractivity profiles from zero-differencing and single-differencing for BDS against the single-differencing results for GPS (zero-differencing GPS data were currently not available). A reasonably high consistency of the BDS- and GPS-derived RO profiles is found in that the BDS refractivities both from zero- and single-differencing appear essentially unbiased against the GPS refractivities within 5 to 25 km. Also the standard deviation is found within about 2 % in this core height range. Future more refined GNOS data processing and analysis will clearly allow further improvement of this consistency, including higher up into the stratosphere, from improvements to both BDS RO and GPS RO processing, and work towards this goal is ongoing.

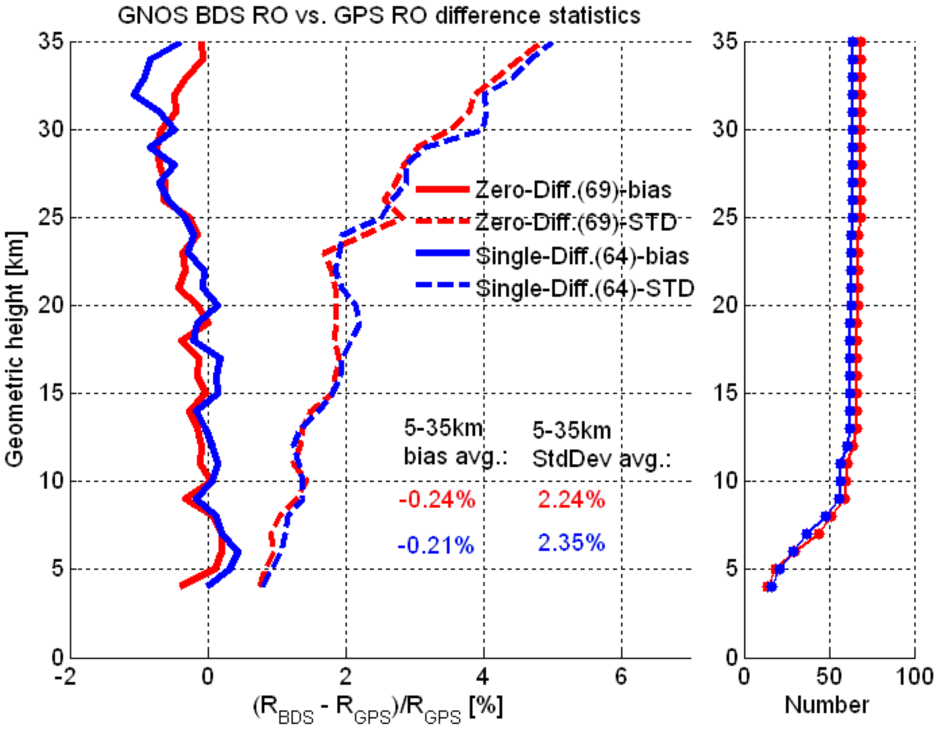

Figure 6. Mean difference (bias) and standard deviation (STD) statistics of GNOS-derived refractivity (R) profiles retrieved based on the zero-differencing (red) and single-differencing (blue) methods, from an ensemble of BDS RO profiles collocated with GPS RO profiles (±200 km / ±1 h collocation criterion; outlier quality control with max. 8 % deviation to ECMWF within 5–35 km, leading to slightly more collocations for the zero-differencing data). Bias (solid) and STD (dashed) profiles as well as the number-of-event profiles (small right-hand-side panel) are shown. The legend indicates the average bias and STD values within 5–35 km.

For producing the statistical validation analysis results compared to the independent reference data, we calculated the fractional error of the retrieved bending angle (α) and refractivity (R) profiles in the form,

$$E_{\alpha} = 100 \times \frac{\alpha - \alpha_{ref}}{\alpha_{ref}} \ [\%] \ , \qquad (11)$$

$$E_{R} = 100 \times \frac{R - R_{ref}}{R_{ref}} \ [\%] \ , \qquad (12)$$

where E denotes the estimated fractional error profiles (against the reference data) for which ensemble estimates of biases (Bias) and standard deviations (StdDev) are illustrated in the result figures. For retrieving bending angle and refractivity profiles from our excess phase data we employed the radio occultation processing package ROPP from the European ROM SAF consortium (Offiler, 2008).

As reference data we used analysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) as well as radiosonde data obtained from the global radiosonde archive of the National Oceanic and Atmospheric Administration–National Centers for Environmental

Information (NOAA-NCEI).

The ECMWF analysis data were used as 6-hourly fields (00, 06, 12, 18 UTC time layers every day) at a horizontal resolution of about 300 km and with 137 vertical model levels (yielding about 0.5 km to 1.5 km resolution over the upper troposphere/lower stratosphere domain of interest). Vertical profiles co-located with the GNOS RO profiles were extracted from these fields by bi-linear interpolation in latitude and longitude to the mean RO event location, using the nearest-neighbor time layer of the RO event time. Since the GNOS data were not assimilated into the ECWMF system the data are clearly independent.

The radiosonde profiles were about 0.5 km to 3 km vertical resolution over the domain of interest, and were used with a ±1 deg lat-lon / ±1 hour collocation criterion to the RO event. The latter criterion pairs the data sufficiently close horizontally in order to ensure reasonably low representativeness error (e.g., Hajj et al., 2004; Anthes et al., 2008).

4 GNOS BDS RO single-difference and zero-difference results analysis

The target domain for the comparative statistical analysis is from 5 km to 35 km height (upper troposphere and lower stratosphere, UTLS), since commonly the data quality above 35 km and below 5 km is less good, due to the ionospheric effects and tropospheric multipath effects, respectively (e.g., Scherllin-Pirscher et al., 2011a, 2011b; Steiner et al., 2013). We first inspect difference statistics to ECMWF and subsequently to radiosondes.

4.1 Comparison analysis of bending angle with ECMWF data

Figure 7 shows the statistics of the GNOS BDS RO bending angle results, for the different BDS subsystems (GEO, IGSO, MEO) and the full BDS (Total), for both single-differencing (Fig. 7a) and zero-differencing (Fig. 7b). The Bias and StdDev profiles have been calculated from the large ensembles of these event datasets, based on the fractional difference profiles according to Eq. (11). In line with expectations, the biases and standard deviations are slightly smaller for the zero-differencing than for the single-differencing (though even smaller standard deviation might be expected from avoiding the reference link computation; e.g., Schreiner et al., 2010) but in general they are very similar. Both cases show a small negative bias of around –0.15 % against ECMWF, and a standard deviation of around 1.5%. At least part of the bias is likely from slight differences in vertical geolocation of GNOS and reference profiles, for which ensuring rigorous consistency is a subtle process (Scherllin-Pirscher et al., 2017). Likewise, part of the standard deviation is from representativeness error between the GNOS and ECWMF profiles, since even though being co-located in mean location they have different detailed locations and resolutions (Foelsche et al., 2011b; Scherllin-Pirscher et al., 2011b).

Several aspects of small differences visible (e.g., specific difference of GEO results from the other results, increasing StdDev differences below 10 km) will be clarified by detailed excess phase processing and retrieval error analyses as part of follow-on work. Regarding the larger deviation of the GEO results in general, these may be related to the fact that the GEO orbit determination is more challenging as well as to the limited geographical coverage of these RO events, with event locations at high latitudes beyond 60 °only (see Figure 5).

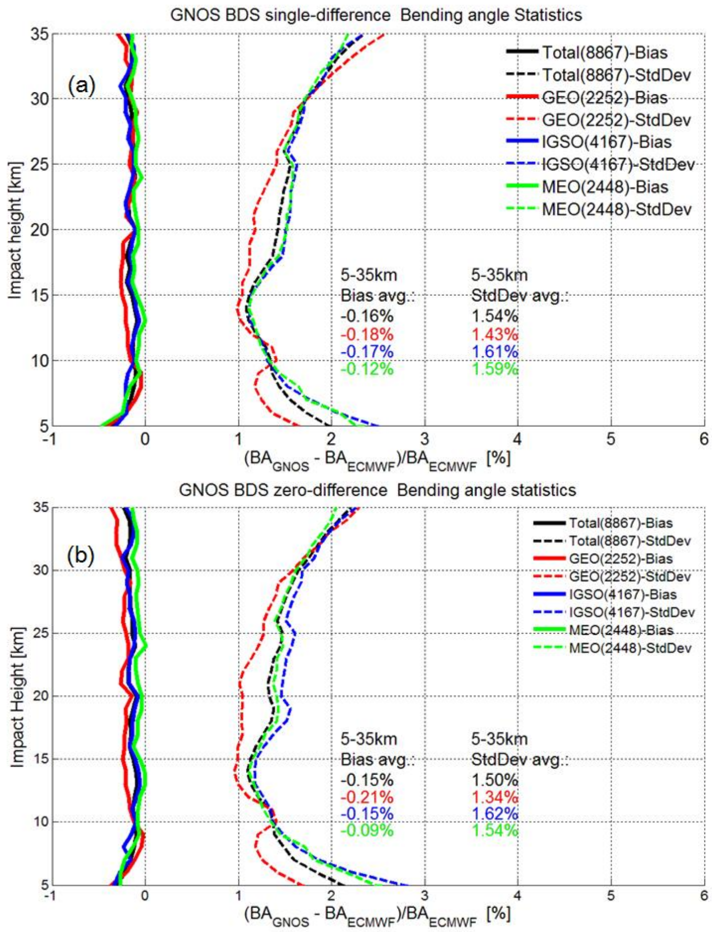

Figure 7. Mean difference (Bias) and standard deviation (StdDev) statistics of the GNOS bending angle profiles retrieved by using excess phases from the single-difference processing **(a)** and the zero-difference processing **(b)**, respectively, with the co-located ECMWF bending angle profiles used as reference. Bias (solid) and StdDev (dashed) profiles are shown for the set of all BDS RO events (black), and the subsets of BDS-GEO (red), BDS-IGSO (blue), and BDS-MEO (green). Legends also indicate the numbers of events involved (the joint set of RO events from both the single- and zero-difference processing) and the average Bias and StdDev values over the 5–35 km range.

Overall the results confirm a high quality of the GNOS retrievals, in line with recent results by Liao et al. (2016), and a robust zero-difference processing being a viable alternative for the single-difference processing. The results also indicate that the BDS retrievals can achieve a quality comparable to what is well established for GPS retrievals. Thanks to the diversity of BDS orbits, we can also demonstrate RO retrievals from occultations with GNSS transmitters not in medium Earth orbit (MEO). The results clearly indicate that also the GNSS transmitters in GEO and IGSO can provide a quality comparable to the ones in MEO.

4.2 Comparison analysis of refractivity with ECMWF data

Figure 8 shows the statistics of the GNOS BDS RO refractivity results, again for the different BDS subsystems (GEO, IGSO, MEO) and the full BDS (Total), for both single-differencing (Fig. 8a) and zero-differencing (Fig. 8b). The Bias and StdDev profiles have been calculated from these large BDS event ensembles based on the fractional refractivity difference profiles according to Eq. (12).

Similar to the bending angle results (Figure 7), the biases and standard deviations for the refractivity results are a bit smaller for the zero-differencing than for the single-differencing but are otherwise quite similar. Both cases show a small negative bias of around –0.05 % against ECMWF, and a standard deviation of near 0.8 % (single-differencing more near 0.9 %). This reduction of bias and standard deviation magnitudes compared to the bending angle (by about a factor of two) is due to the filtering properties of the Abelian integral that transforms the bending angle to refractivity profiles (Rieder and Kirchengast, 2001; Scherllin-Pirscher et al., 2011a; Schwarz et al., 2017).

As for the bending angles, also aspects of small differences visible here for refractivity, such as again more deviation of the GEO results, will be explored by detailed excess phase processing and retrieval error analyses as part of follow-on work.

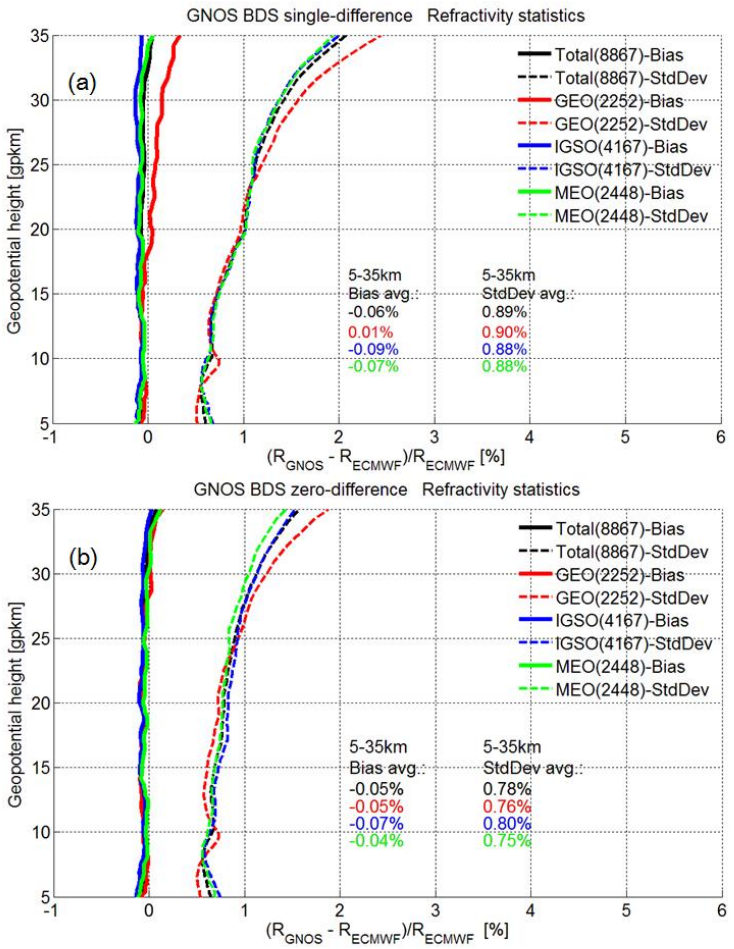

Figure 8. Mean difference (Bias) and standard deviation (StdDev) statistics of the GNOS refractivity profiles retrieved by using excess phases from the single-difference processing **(a)** and the zero-difference processing **(b)**, respectively, with the co-located ECMWF refractivity profiles used as reference. Same layout as Figure 6; see that caption for further description.

Overall the refractivity results confirm the messages summarized in Sect. 4.1 based on the bending angle results. That is, they underline the high quality of the GNOS BDS retrievals as being (nearly) comparable to GPS retrievals, the robustness of both the zero- and single-difference processing, and the reliable retrieval quality also for the RO events with GNSS transmitters not only on MEO satellites but also on GEO and IGSO satellites.

4.3 Comparison analysis of refractivity with radiosonde data

Figure 9 shows the single- and zero-difference results for refractivity statistics, again Bias and StdDev profiles, here against collocated radiosonde profiles and only for the whole set of BDS RO events, since the number of collocations is more limited. The number of RO events entering into the statistics is also strongly height-dependent in this case and is therefore shown not only as (maximum) number in the legend but also as height profiles in a side panel (Figure 9, right).

Given the smaller ensemble size of about 50 to 200 events (depending on height) and the less strict collocation, and thus somewhat higher representativeness error than for the ECMWF data extracted at the mean RO event location, these refractivity results are expected to exhibit somewhat more deviations than those in Figure 8. As Figure 9 shows, the bias is nevertheless still fairly small, near –0.3 %, and the standard deviation is near 0.95%, i.e., still below 1 %.

In summary, also the comparison to this entirely independent radiosonde dataset underpins the finding that both the zero- and single-differencing do a robust job and that the GNOS BDS retrievals can provide a high performance similar to GPS retrievals that have been established earlier to compare well to quality radiosondes (Anthes, 2011; Ladstaedter et al., 2015).

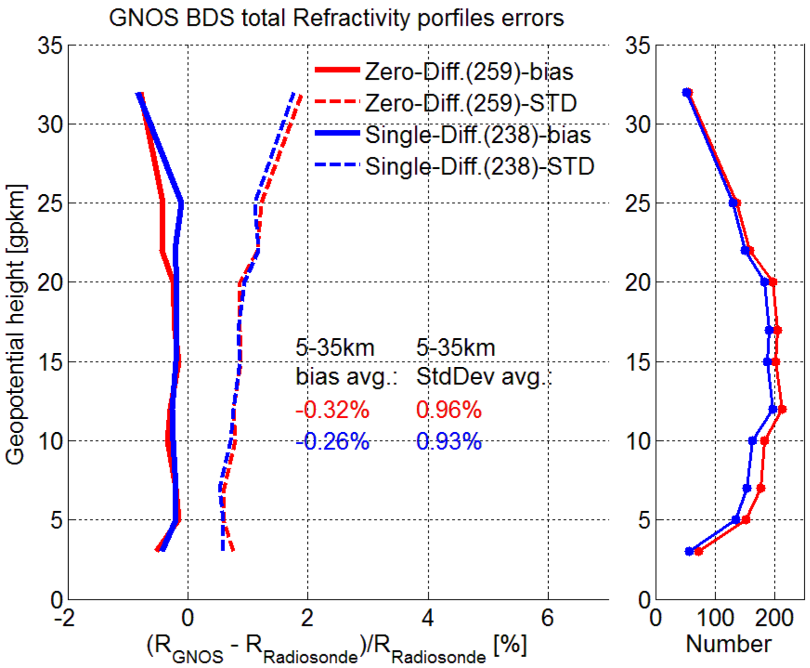

Figure 9. Mean difference (Bias) and standard deviation (StdDev) statistics of the GNOS refractivity profiles retrieved by using either zero-differencing (red) or single-differencing (blue), with collocated radiosonde refractivity profiles used as reference (±1 lat-lon / ±1 h collocation criterion). Bias (solid) and StdDev (dashed) profiles as well as the number-of-event profiles (small right-hand-side panel) are shown for the total set of BDS RO events. The legends also indicate the numbers of events involved and the average Bias and StdDev values within 5–35 km.

5 Conclusions

In this study we have introduced our single- and zero-difference excess phase processing of BeiDou System (BDS) RO data of the FY-3C GNOS mission and evaluated the quality of atmospheric profiles derived based on this single- and zero-difference processing.

The Single-differencing can correct the receiver clock offset, thus it has lower requirements on the receiver clock stability. However, it requires a proper reference GNSS satellite and will induce some of this reference satellite's positioning and carrier phase measurement errors into the RO processing. The advantage of the zero-difference algorithm is its independence from reference satellites, but it requires a receiver clock of very high quality (ultra-stable oscillator such as available for GNOS) to obtain a highly accurate receiver clock offset estimate, which nevertheless can leave some residual errors after the clock offset correction.

Because BDS currently still is a regional navigation system, we found that about 20 % of the GNOS BDS RO events do not have proper reference satellites for single-differencing, providing another argument for a zero-difference alternative. We performed a comparative analysis of the zero-difference and single-difference excess phase processing chains for the FY-3C GNOS BDS RO observations, in which independent reanalysis data from ECWMF and collocated high-quality data from radiosondes have been used as reference for evaluating the retrieved bending angle and refractivity profiles over the upper troposphere and lower stratosphere (UTLS, 5 km to 35 km).

The results showed that the GNOS BDS RO profiles derived by using both the zero-difference and single-difference algorithms exhibit very good consistency with the ECMWF and radiosonde data. The zero-difference method appeared to perform slightly better than the single-difference method, especially visible at stratospheric altitudes (above 15 km).

Comparing to ECMWF data, the average UTLS bending angle bias was found near –0.15 % and the associated average standard deviation near 1.5 %; the average refractivity bias was accordingly found as small as around –0.05 % and the associated standard deviation at about 0.8 %. Comparing to radiosonde data, the GNOS BDS RO refractivity profiles both from zero- and single-difference processing also showed high consistency, with the average refractivity bias in the UTLS found near –0.3 % and the associated standard deviation near 0.95 %, i.e., also below 1 %, despite increased representativeness error in this latter comparison.

Overall these results indicate high quality of the GNOS BDS retrievals, and a robust zero-difference processing that is a viable alternative for the single-difference processing. The results also indicate that the BDS retrievals can achieve a quality comparable to the established GPS retrievals. Based on the diversity of BDS orbits, we also demonstrated for the first time RO retrievals from occultations with GNSS transmitters not in MEO. We found that also the GNSS transmitters in GEO and in IGSO provide a quality comparable to the ones at MEO satellites.

Currently, the GRAS onboard the European meteorological satellite series MetOp and the GNOS occultation receiver onboard the Chinese meteorological satellite series FY-3 are the two RO instruments for long-term operational observations that include an ultra-stable crystal oscillator featuring a very high-quality Allan deviation at the 10^{-12} second accuracy level. In the future, additional RO missions such as COSMIC-2, MetOp-SG, and advanced-GNOS instruments will expand on this high-quality basis. For these operational backbone missions, leading the field with their data quality, the zero-difference method will generally perform better and will thus likely replace the single-difference method in the future.

Acknowledgements
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