Reply to referee #2

We would like to acknowledge the referee support for the manuscript and took into account the suggested minor revisions. In the revised manuscript are corrected a number of commas and typos. To improve the readability of the manuscript small changes in the wording are introduced and listed below. Please note, that changes number 38) and 46) were suggested in personal communication with dr. Florian Zus.

1) On page 1 line 5
… a well-established research field.

changed to
…a well-established research field in both research and operation.

2) On page 3 line 1-2
One of them is the International GNSS Service (IGS, http://www.igs.org). At present, IGS provides among other wide range of satellite (orbit and clocks) and tropospheric products.

changed to
Of primary importance is the International GNSS Service (IGS, http: //www.igs.org). At present, the IGS provides a wide range of satellite (orbit and clocks) and tropospheric products essential for GNSS Meteorology.

3) On page 3 line 9-10
The upper part of the atmosphere is a dispersive medium which influence can be more or less eliminated by combining observations at two GNSS L-band frequencies in the range from 1.16 GHz to 1.61 GHz.

changed to
The upper part of the atmosphere is a dispersive medium, the influence of which can be more or less eliminated by combining observations from the two GNSS L-band frequencies in the range from 1.16 GHz to 1.61 GHz.

4) On page 3 line 200
… meteorologic data…

changed to
… meteorologic observations…

5) On page 4 line 10-11
Since ZWD is a mainly a function of partial water vapour pressure e and the temperature T , it can be calculated with a numerical integration through a full profile of these meteorological parameters together with the two refractivity constants k2′ [K/hP a] and k3 [K2/hP a]…

changed to
Since ZWD is a mainly a function of partial water vapour pressure (e) and the temperature (T), it can be calculated with a numerical integration through a full atmospheric profile using these two meteorological parameters together with the two refractivity constants k2′ [K/hP a] and k3 [K2/hP a] …

6) On page 4 line 16-17
Firstly, the capability of estimating tropospheric parameters from GNSS with a high spatial and temporal resolution, a low latency, is of high interest for meteorology.

changed to

Firstly, the capability of estimating tropospheric parameters from GNSS with a high spatial and temporal resolution and low latency, is of great interest to meteorology.

7) On page 5 line 8-10
The main purpose of the E-GVAP project is to collect and distribute NRT (within 90 min) GNSS derived ZTDs for usage in operational weather forecasting, to monitor data quality and attempt to expand the GNSS meteorological network in a collaboration between meteorology and geodesy.

changed to
The main purpose of the E-GVAP project is to collect and distribute GNSS derived ZTDs for usage in operational weather forecasting in NRT (within 90 min), to monitor data quality and attempt to expand the GNSS meteorological network in a collaboration between meteorology and geodesy.

8) On page 5 line 13-14
…Precise Network Positioning (PNP)…

changed to
…"network"…

9) On page 5 line 19
…global products in support of PPP.

changed to
…global orbit and clock products in support of PPP.

10) On page 5 line 27
Tropospheric products of real-time PPP…

changed to
Tropospheric products derived from real-time PPP…

11) On page 6 line 33
… above a GNSS receiver…

changed to
… above the GNSS antenna …

12) On page 7 line 3
… the atmospheric loading effect based on actual meteorological data…

changed to
… atmospheric loading based on actual meteorological data…

13) On page 7 line 5-6
Other emerging fields for exploiting …

changed to
Other emerging fields requiring exploitation of …

14) On page 7 line 9
… the troposphere product…

changed to
… the provision of the tropospheric product…

15) On page 7 line 20-24

Until 2003, the ZTD estimates consisted in a combined product derived from the contribution of the routinely produced ZTDs of several IGS analysis centres (Gendt, 1998). Due to large inconsistencies among analysis centres and changes over time in the estimation processes the legacy combination product was abandoned in 2003 to the profit of a new ZTD product derived from PPP processing by one centre (Byun and Bar-Sever, 2009).

changed to
Until 2003, ZTD estimates consisted as a combined product derived from the contribution of the routinely produced ZTDs from several IGS ACs (Gendt, 1998). Due to large inconsistencies among analysis centres and changes over time in the estimation processes, the legacy combination product was abandoned in 2003 and was replaced with a new ZTD product derived from PPP processing by one AC (Byun and Bar-Sever, 2009).

16) On page 7 line 31
… but with a different software…

changed to
… but with Bernese software …

17) On page 7 line 34
… GNSS ACs in Europe…

changed to
… European ACs …

18) On page 8 line 13
Remote sensing of water vapour techniques may be divided into two categories:…

changed to
Techniques capable of remote sensing atmospheric water vapour can be divided into two categories:…

19) On page 9 line 25
While much of the work of usage of GNSS data in weather forecasting is taking place at the National Meteorological Services (NMS)…

changed to
While much of the work regarding application of GNSS data in weather forecasting is taking place at the National Meteorological and Hydrological Services (NMHS)…

20) On page 10 line 3-4
…, to suit local needs,..

changed to
… to suit local requirements…

21) On page 10 line 21
… GNSS tropospheric products comparison with NWP models in Europe…

changed to
… GNSS tropospheric products and NWP models in Europe…

22) On page 10 line 22
… being largest in summer…

changed to

… with largest errors in summer…

23) On page 11 line 25-26
Reported is also systematic underestimation of the NWP model diurnal IWV cycle…

changed to
Also reported is a systematic underestimation of NWP diurnal IWV cycle…

24) On page 11 line 1-4
… the period inside which the observations are selected, is taken into account, and that a time sequence of observations from a site can be used, while only one in 3D-Var. 4D-Var is mainly used for global models, with wide assimilation time windows, 6-12 hours, but in some cases also in regional models with more narrow assimilation windows.

changed to
…(i.e. the period inside in which the observations are selected), is taken into account, and that a time sequence of observations from a site can be used, while only one observation is used in 3D-Var. At present time, 4D-Var is mainly used for global models, with wide assimilation time windows (e.g. 6-12 hours), but in some cases it is also used in regional models with more narrow assimilation windows.

25) On page 11 line 16
… "now" …

changed to
… present time …

26) On page 11 line 20
… converting to IWV…

changed to
… converting ZTD to IWV…

27) On page 12 line 2
But sometimes negative effect were seen…

changed to
Occasionally negative effect are observed…

28) On page 12 line 6-7
… but it is expected that many more will follow in the next few years.

changed to
… and it is expected that many more will follow in the near future.

29) On page 12 line 12-13
… in which case they'll need to rely more heavily on specific frequent fast access observations, such as sub-hourly GNSS delays (de Haan, 2013).

changed to
… in which case the RUC model will need to rely more heavily on specific frequent fast access observations, such as from sub-hourly GNSS (de Haan, 2013).

30) On page 12 line 16-19
Schemes for variational bias control are being introduced and tested in both AROME (Moll et al., 2008) and HARMONIE (Arriola et al., 2016). Variational bias control enables usage of time varying

biases in the DA, which is likely a benefit, since errors and biases are likely weather dependent. It is well established the O-B offsets have a seasonal dependence.

changed to
Schemes for VAR bias control (BC) are being introduced and tested in both AROME (Moll et al., 2008) and HARMONIE (Arriola et al., 2016) NWP models. VAR BC enables use of temporally variable biases in the DA, which is likely a benefit, since errors and biases are often weather dependent. It is also well established that O-B offsets have a seasonal dependence.

31) On page 12 line 20-23
There is a huge range of NWP resolutions involved, grid box sizes running from about 60 km (ARPEGE on far side of the Earth seen from Paris) to 1.5 km in the latest UK Met Office local model. Many NMSes now run their high resolution models at about 2.5 km grid box size (AROME, COSMO, HARMONIE), many will move toward 1 km in the coming years.

changed to
There is a huge range of NWP resolutions involved, grid box sizes range from ˜ 60 km (ARPEGE on the far side of the Earth viewed from Paris) to 1.5 km in the latest UK Met Office local model. Many NMHSs now run their high resolution models 30 with a ˜ 2.5 km grid box size (AROME, COSMO, HARMONIE), and many will move toward 1 km resolution in the near future.

32) On page 12 line 25-26
This increased the amount of sites used by a factor 4, and improved the forecasting skill of the AROME model at Météo France (Moll et al., 2008).

changed to
This increased the number of sites assimilated by a factor 4, and measurably improved the forecasting skill of the AROME NWP model at Météo France (Moll et al., 2008).

33) On page 12 line 28-29
… will benefit strongly from more of these observations. Indicating that we are far from saturation as regards the density of GNSS sites in the system.

changed to
will benefit strongly from more of these type of observations, and also indicating that we are far from saturation as regards the density of GNSS observations in the system.

34) On page 13 line 5
… they will get a higher influence on the DA…

changed to
… the data will have a higher influence on DA …

35) On page 13 line 11
Assimilation of ZTD gradients and STD appears a natural next step in NWP usage of GNSS data.

changed to
Assimilation of ZTD gradients and STD appears to be a natural next step in the NWP use of GNSS tropospheric observations.

36) On page 13 line 16-17
… too large analysis increments. This could be reduced by reducing their weighting, to correct for error correlations between numerous slants from a single receiver.

changed to

… too large analysis increments, however the increments could be reduced by reducing their weighting to correct for error correlations between numerous slants from a single receiver.

37) On page 13 line 16-17
An earlier comparison of GNSS to NWP STDs was carried out by de Haan et al. (2002).

changed to
Added line in table 4:
NWP model: HIRLAM Compared Parameters: SWD Reference: de Haan et al (2002)

38) On page 13 line 20
Zus et al. (2008) implemented a slant assimilation capability to the 4D-Var MM5 model and verified its functionality. The representation of model physics and horizontal diffusion in 4D-Var were found to be very important factors. In the assimilation experiments it was found that the assimilation improved O-B statistics and resulted in a reasonable impact on the analysis, which was confirmed by data from independent GNSS receivers and radiosondes. A comparison to weather radar data showed improved simulation of a convective system. Use of "simplified" physics in the 4D-Var MM5 model led to erroneous analyses.

changed to:
Zus et al. (2011) implemented a STD assimilation capability to the 4D-Var MM5 model and verified its functionality. Assimilation experiments indicate that the impact on the precipitation forecast is weak, but positive.

39) On page 13 line 25-26
Since COST-716 and TOUGH, the typical NWP resolution at operational NMSs has increased significantly. This is likely to benefit use of asymmetrical GNSS information, such as ZTD gradients and STD, in NWP DA schemes.

changed to
Since COST-716 and TOUGH, the typical NWP resolution at operational NMHSs has increased significantly and is likely to benefit from use of asymmetrical GNSS products, such as ZTD gradients and STD estimates.

40) On page 13 line 31-32
Over the last years, several publications discussed the use of GNSS for studying the water vapour field, and the production of GNSS-based tailored products for severe weather event monitoring (Table 6).

changed to
Over the last few years, several publications discussed the use of GNSS for studying water vapour field evolution, and the production of GNSS-based products tailored for severe weather event monitoring (Table 6).

41) On page 14 line 6-7
… rapidly changing over time. They can also be initiated due to the orography causing large transfer of water vapour amount e.g. between the plain and the mountains (Graham et al., 2012),…

changed to
changing rapidly over time. They can also be initiated due to the orography causing a large transfer of water vapour e.g. between plains and mountainous regions (Graham et al., 2012),…

42) On page 14 line 15-17
… these authors obtained clear evidences of the benefits that GNSS can bring to the monitoring of severe weather events. They also often mention that further research and developments are

needed to improve and standardise their methods and to be able to use them in operational nowcasting.

changed to
all these authors obtained clear evidence of the benefits that GNSS can bring to the monitoring of severe weather events. They also often mention that further research and developments are required to improve and standardise their methodology and to be able to allow use in operational nowcasting at NMHSs.

43) On page 16 line 28
… require another grid than small limited area networks.

changed to
… require different grid to small limited-area networks.

44) On page 16 line 31-33
… more than 50 km at an elevation of 10○ and a height of 10 km. Extending grids around small networks is therefore a strategy to process STDs at low elevations, which provide most information about the vertical structure.

changed to
… > 50 km at an elevation of 10○ and a model height top of 10 km. Extending grids around small networks is therefore a strategy to process STDs at low elevations, which provides most of the information regarding the vertical structure.

45) On page 17 line 13-14
… along the path. This leads to a much more realistic mapping from the grid to the STD and the error of the discretization is reduced (Perler et al., 2011).

changed to
… along the path, leading to much more realistic mapping from the grid to the STD and the error of the discretization is reduced (Perler et al., 2011).

46) On page 17 line 15
A non-linear operator which takes the ray bending into account could be developed using a ray-tracer (Zus et al., 2012).

changed to:
More recent Zus et al., 2015 developed operators which are both fast and accurate taking ray-bending into account and are thus tailored for variational data assimilation/travel time tomography.

47) On page 18 line 8
… done…

changed to
… achieved…

48) On page 18 line 18-19
Pseudo observations are built from real observations and some physical models…

changed to
Pseudo-observations are a combination of real observations and physical models…

49) On page 18 line 23
Extra data have usually a stabilizing effect on the inversion and act like constraints.

changed to
Extra data usually has a stabilizing effect on the inversion in the same manner as constraints.

50) On page 18 line 24-26
Using a carefully tuned tomography system continuous series of stable results could be obtained which provide important information of the temporal development of the humidity filed…

changed to
Using a carefully tuned tomography system, continuous series of stable results can be obtained providing important information of the temporal evolution of humidity fields …

51) On page 18 line 29-30
… late 90th (Braun et al., 1999; Foelsche, 1999) describing the setup and results of rather small GPS networks.

changed to
… late 1990's (Braun et al., 1999; Foelsche, 1999), describing the setup and results of rather small localized GPS networks.

52) On page 19 line 5-6
However, the future prospects of GNSS tomography are encouraging. Regarding the development of GNSS sites processed by E-GVAP…

changed to
The future prospects of GNSS tomography however are encouraging. Regarding the development the number of GNSS sites 15 processed by E-GVAP…

53) On page 19 line 7
… the quality of STD data becomes sufficient in a near future.

changed to
… the quality of STD data becomes sufficient for GNSS tomography in the near future.

54) On page 19 line 10
… way.

changed to
… manner.

55) On page 19 line 21
… in the IWV from radiosonde measurements…

changed to
…in IWV obtained from radiosonde observations …

56) On page 20 line 12-14
Vey et al. (2009) also investigated the homogeneity of the long-term GPS IWV series, and showed that offsets up to ± 1 kg/m2 can arise, due to changes in antennas and radomes, and due to sudden changes in the number of observations, usually associated with failures in the equipment or changes in the observation cut-off angle.

changed to
Vey et al. (2009) also investigated the homogeneity of long-term GPS IWV time series, and found offsets of up to ± 1 kg/m2 due to antenna and radome changes, and due to sudden changes in the number of observations, usually associated with failures in equipment or changes in the observation cut-off angle used in the GNSS processing.

57) On page 20 line 31
Application of GNSS for atmospheric sounding is now a well-established technique in Europe.

changed to
The meteorological application of GNSS is now a well-established technique in Europe.

58) On page 21 line 3-4
Advanced GNSS tropospheric products such as horizontal ZTD gradients, STD (delays in the direction of each satellite), and 3D refractivity or humidity fields (using tomographic reconstruction) can now be produced.

changed to
Advanced GNSS tropospheric products such as horizontal ZTD gradients, STD (delays in the direction of each satellite), and 3D refractivity or humidity fields (using tomographic reconstruction) can now be produced. ZTD gradients and STD can be derived for receivers independently of their spatial density, while tomography requires input from a dense network in order to function well.

59) On page 21 line 16
The application of GNSS tropospheric products for climate monitoring is an emerging field of research.

changed to
deleted from the text

60) On page 21 line 20-22
Ongoing reprocessing efforts within the IGS and EUREF, using state-of-the-art GNSS processing, will provide a consistent time series of tropospheric data, taking benefit of nearly 20 years of GNSS observations from over 400 stations worldwide.

changed to
Ongoing reprocessing efforts within the IGS and EUREF using state-of-the-art GNSS processing will provide a consistent time series of tropospheric data.

61) On page 31 in table 2
Precise Network Positioning (PNP)

changed to
Network solution

62) On page 31 in table 2 title
PPP vs PNP GNSS processing strategy.

changed to
PPP vs Network GNSS processing strategy