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Total Carbon Column Observing Network Philippines: toward quantifying atmospheric carbon in Southeast Asia

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Abstract

TCCON (Total Carbon Column Observing Network) is dedicated to the precise measurements of greenhouse gases such as CO₂ and CH₄. TCCON measurements are used extensively for satellite validation, for atmospheric chemistry modeling, and for carbon cycle studies. With the global effort to cap greenhouse gas emissions, TCCON has taken on a vital role in validating past, current, and future satellite missions such as Japan's Greenhouse Gases Observing Satellite (GOSAT & GOSAT-2), National Aeronautics and Space Administration's (NASA) Orbiting Carbon Observatory-2 (OCO-2 & future OCO-3), and others. However, the lack of reliable validation data for satellite-based greenhouse gas observations in the tropics is a common limitation in global carbon-cycle studies that have a tropical component. The international CO₂ modeling community has specified a requirement for expansion of the CO₂ observation network within the tropics in order to reduce uncertainties in regional estimates of CO₂ sources and sinks. A TCCON site in the tropical western Pacific is a logical next step in obtaining additional knowledge that would greatly contribute to the understanding of the Earth's atmosphere and the carbon cycle. In this study, we present an assessment of a planned site in the Philippines where a new TCCON station, the first in Southeast Asia, will be installed.

Keywords

total, asia, carbon, column, atmospheric, observing, southeast, network, philippines:, toward, quantifying

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Total Carbon Column Observing Network Philippines: Toward quantifying atmospheric carbon in Southeast Asia

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Abstract

TCCON (Total Carbon Column Observing Network) is dedicated to the precise measurements of greenhouse gases such as CO₂ and CH₄. TCCON measurements are used extensively for satellite validation, for atmospheric chemistry modeling, and for carbon cycle studies. With the global effort to cap greenhouse gas emissions, TCCON has taken on a vital role in validating past, current, and future satellite missions such as Japan's Greenhouse Gases Observing Satellite (GOSAT & GOSAT-2), National Aeronautics and Space Administration's (NASA) Orbiting Carbon Observatory-2 (OCO-2 & future OCO-3), and others. However, the lack of reliable validation data for satellite-based greenhouse gas observations in the tropics is a common limitation in global carbon-cycle studies that have a tropical component. The international CO₂ modeling community has specified a requirement for expansion of the CO₂ observation network within the tropics in order to reduce uncertainties in regional estimates of CO₂ sources and sinks. A TCCON site in the tropical western Pacific is a logical next step in obtaining additional knowledge that would greatly contribute to the understanding of the Earth's atmosphere and the carbon cycle. In this study, we present an assessment of a planned site in the Philippines where a new TCCON station, the first in Southeast Asia, will be installed.

Keywords: TCCON · satellite validation · capacity building · atmospheric processes · carbon cycle

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Introduction

The United Nations' World Risk Report 2016 ranked the Philippines third among countries most vulnerable to natural disasters (e.g., effects of climate change), after Vanuatu and Tonga (Garschagen et al., 2016). This is because the Philippines is highly exposed to natural hazards coupled by significant social vulnerabilities (Wannewitz, Hagenlocher, & Garschagen, 2016). Natural disasters common to the Philippines include earthquakes, volcanic eruptions, tsunamis, and other events that could be exacerbated by climate change such as flooding, typhoons, storm surges, landslides, and erosion.

Although the Philippine government has recently stepped up the country's infrastructure, civil protection, and general disaster preparedness, these alone are not sufficient without strong, internationally-supported climate change policies. To aid in policy-making, better quantification of greenhouse gas sources and sinks is needed. Southeast (SE) Asia, a region most affected by climate change, is also one of the regions with the largest uncertainties in carbon sources and sinks. For example, results of global inverse modeling showed that the largest uncertainties in CH_4 fluxes are in East and SE Asia (Cressot et al., 2014).

Carbon dioxide (CO_2) and methane (CH_4) are the two major anthropogenic greenhouse gases that contribute to climate change (IPCC, 2013). To answer the need for better quantification of greenhouse gas sources and sinks, new space-borne satellite instruments with unprecedented measurement precision and accuracy have been launched. After the successful launch of Japan's Greenhouse Gases Observing Satellite (GOSAT) in 2009 by the Japanese Space Agency (JAXA) (Kuze, Suto, Nakajima, & Hamazaki, 2009; Nakajima, Kuze, & Suto, 2012), National Aeronautics and Space Administration (NASA) launched Orbiting Carbon Observatory-2 (OCO-2) in 2014 (Kuang, Margolis, Toon, Crisp, & Yung, 2002; Crisp et al., 2004; Miller et al., 2007; Boesch, Baker, Connor, Crisp, & Miller, 2011). GOSAT's successor, GOSAT-2, will continue this important mission and is planned to be launched into orbit by the Japanese fiscal year of 2017 (FY2017). Together with modeling studies, these measurement platforms are aimed at achieving a better understanding of sources and sinks of greenhouse gases like CO_2 and CH_4 .

However, these satellite instruments, no matter how advanced, will have to be validated by ground-based measurements. The lack of data in the tropics is a major challenge in satellite validation programs. Total Carbon Column Observing Network (TCCON) (Wunch et al., 2011) is the current "gold standard" for the total column measurements of CO_2 and CH_4 . Currently, there are 23 operational TCCON sites across the globe (Figure 1), but due to logistical difficulties, budget restrictions, and lack of site support, the distribution is uneven—leaving gaps in very important regions from

an atmospheric science perspective. For example, Figure 1 demonstrates a big gap of TCCON coverage centered around the Philippines, extending all the way from the Indian Ocean to the Tropical Western Pacific (TWP). And yet, SE Asia is a region where some of the world's most important atmospheric processes take place.

Figure 1. Operational TCCON stations worldwide (red) as of 2015. Figure courtesy of D. Feist, Max Planck Institute – Jena, Germany.

The SE Asian region is the preeminent source of tropospheric air entering the tropical stratosphere (Wright, Fu, Fueglistaler, Liu, & Zhang, 2011). According to Wright et al., (2011) "the temperature imprint carried by water vapor entering the stratosphere is disproportionately set by conditions in the tropopause layer above SE Asia" (shown in Figure 2 of Wright, Fu, Fueglistaler, Liu, & Zhang, 2011). Recent research results by Rex et al. (2014) show that an atmospheric hydroxyl radical (OH) minimum (or "OH hole") over the TWP is allowing more ozone-depleting chemicals into the stratosphere, which would amplify ozone depletion in the polar regions. This could have a significant influence on the climate of the Earth. OH acts like an atmospheric cleansing agent, removing pollutants from the atmosphere. The Philippines is located right at the edge of this OH hole and the transit region (or "giant elevator") into the stratosphere.

The lack of data in the tropical regions is also a common limitation in global carbon-cycle modeling studies. The international CO_2 modeling community have specified a requirement for the "expansion of the CO_2 observation network within the tropics" to reduce uncertainties in regional estimates of CO_2 sources and sinks using atmospheric transport models (Gurney et al., 2002). A TCCON site in the tropical regions, like the tropical western Pacific, is a logical next step in obtaining additional knowledge that would greatly contribute to the understanding of the earth's atmosphere and the carbon cycle.

This collaborative project among the University of Wollongong (UOW, Australia), the National Institute for Environmental Studies (NIES, Japan) and the Energy

Development Corporation (EDC, Philippines) is dedicated to respond to the need for a ground-based station in the SE Asian region, with the primary purpose of validating the future GOSAT-2 mission. Additionally, the Philippine site will be able to provide the much-needed validation to current and future partner missions (e.g., NASA's OCO-2 and OCO-3, Europe's Sentinel-5P), as well as data to global scientific partners through TCCON's data usage policy. This will put the Philippines on the global map of important atmospheric observation and satellite validation networks.

Site support from EDC

Energy Development Corporation, a pioneer in the geothermal energy industry with more than three decades of proven success in developing and commercializing renewable energy, will support the planned Philippine TCCON station as part of their effort to better quantify the major anthropogenic greenhouse gases that cause global warming and climate change. The Philippines is a minor emitter of CO₂ compared to most developed countries; for example, from power generation alone, the United States of America emits 80 times more CO₂ than the Philippines (www.carma.org, 2009 estimate). In contrast, the Philippines is the second largest producer of clean geothermal energy in the world (Bertani, 2016), while being one of the most vulnerable countries to climate change-induced natural hazards. This makes climate change research and adaptation to the consequences of climate change of paramount importance to the Philippines. Greenhouse gas observations are scarce in this important part of the globe. As part of its social and environmental commitment, EDC will host a TCCON station in its renewable energy power generating facility in Burgos, Ilocos Norte (Figure 2).

Figure 2. The TCCON container will be placed within the EDC Burgos Wind Farm Project, specifically at the substation site where technical support is available in close proximity.

EDC's environmental commitment and its collaboration with biologists and environmental scientists have led to projects and studies showcasing the flora and fauna of the Philippines and highlight the need to preserve biodiversity in the country (e.g., David, de Jesus, & Barcelona, 2011; de la Paz, Tapan, Doplon, Knipp, & Santiago, 2011; Galang, Mesina, Marciano, Tungol, & Sarmiento, 2012; Fernando, Galindon, & Ong, 2016). Supporting a TCCON station in the Philippines continues and strengthens EDC's commitment toward preservation of natural resources and protection of the environment.

Instruments and Methods for Site Assessment

This section discusses the methods used to assess the chosen location for the TCCON station. In addition to accessibility, clear skies and potential scientific contribution of the region were considered.

Site Description

Burgos is a town located in the northernmost part of Luzon island in the Philippines (18.52°N, 120.65°E), with a population of about 10,000. It is approximately 55 km from Laoag City, the capital of Ilocos Norte Province. Figure 2 shows the location of the future TCCON site.

Satellite XCO₂ Retrievals from GOSAT and OCO-2

For this study, we used GOSAT XCO₂ retrievals from NIES (version 2.xx). The OCO-2 data used are the "lite" version 7B retrievals also described in Wunch et al. (2016). We used the same spatial coincidence criterion for both satellites (400 km radius from the site). Figure 3a shows the GOSAT (cyan circles) and OCO-2 (magenta squares) soundings selected within this spatial domain (white circle). This radius terminates just before the boundaries of Metro Manila and is away from the most densely populated areas. With this criterion, measurements taken over strong CO₂ sources can be avoided and a representative XCO₂ cycle around Burgos can be observed. GOSAT soundings go back to 2010, OCO-2 started measurements in 2014, continuing and complementing the measurements of GOSAT with a finer resolution. To construct a time series of the daily mean XCO₂ within this radius, a daily-mean value was calculated by weighting the satellite measurements according to their associated retrieval errors. This included measurements taken over land and ocean.

Due to the irregular topography of Luzon island (mountains, forests, and rice fields), there are few retrievals available over land, because successful retrievals of CO₂ columns require very accurate knowledge of the light path through the atmosphere and reasonably homogeneous surface reflectance characteristics. This is difficult to achieve over rough terrain. However, there are numerous measurements

Figure 3. (a) Soundings from GOSAT (cyan circles) and OCO-2 (magenta squares) selected within a 400-km radius from Burgos (white circle) and (b) time series of error-weighted daily averaged XCO₂ values within this radius from both satellites. OCO-2 data with Warn Level flags of 11 or better were selected. For Warn Levels definition, see Mandrake et al. (2013).

over the ocean around Burgos using the satellite's glint mode. Glint mode is a technique where the specular reflection of the sun's rays over water is used. This reflection results in a very bright signal and enhances the instrument's ability to acquire highly accurate measurements, particularly over oceans.

Clear Sky Studies

One important criterion in choosing a site for a TCCON station is the clear sky probability at the site. A clear, unobstructed view of the sun is required to take measurements of solar absorption spectra from the ground. Successful soundings from satellites that look down at reflected sunlight on the earth's surface also require cloud-free skies. Therefore, we investigated clear sky probabilities using measurements from existing satellites.

MODIS Data

This study used data from the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments aboard the Aqua and Terra satellites. Considered in these calculations were

pixels with clear sky or cloudy characteristics within a $0.1^\circ \times 0.1^\circ$ square centered at each site within the time frame of representative months.

GOSAT CAI Data

The study also used data from GOSAT's Cloud and Aerosol Imager (CAI, Level 2). It considered 120 overpass measurements over one year (2014) to derive clear sky probabilities within a 500 m x 500 m area (CAI pixel size). The calculations were done by matching the nearest pixels from each CAI frame, where each CAI pixel represented clear (1) or cloudy (0).

Footprint Analysis

To estimate the measurement sensitivity to surface fluxes (here called "footprints") at the TCCON site, the study employed the same method as described in Belikov et al. (2017). Forward simulations for the footprints were derived from the NIES Eulerian three-dimensional transport model (TM). The FLEXPART Lagrangian Particle Dispersion Model (LPDM) was used for backward trajectory

tracking. To initialize backward tracer simulations with the FLEXPART model, the NIES TM CO₂ concentrations, sampled at 1 km above ground at 13:00 local time, were used. FLEXPART considers atmospheric tracers as a discrete phase and tracks the pathway of each individual particle (Stohl et al., 2009). These footprints are also shown in Belikov et al. (2017).

GEOS-Chem Modelling

Footprint analysis was expanded by including GEOS-Chem (Bey et al., 2001) simulations. GEOS-Chem was run at 2°x2.5° horizontal resolution with 47 vertical levels, from January 2010 until April 2016 following a 12-year spin-up period. From 2010 to 2013, GEOS-5 meteorology was used, with GEOS-FP meteorology from the 1st of January 2013 onwards. The GEOS-Chem v10-01 CO₂ simulation is based on Nassar et al. (2010). This simulation used monthly averaged fossil fuel emissions from Open-source Data Inventory for Anthropogenic CO₂ (ODIAC) (Oda & Maksyutov, 2011) (year specific until the end of 2014, with 2015 and 2016 recycling 2014 estimates), the annual inventory of biofuel emissions scaled to 1995 from Yevich and Logan (2003), 2004 monthly shipping emissions from International Comprehensive Ocean-Atmosphere Data Set (ICODS) (Corbett & Koehler 2003, 2004; Endresen et al., 2004, 2007), 2005 aviation fuel burn emissions from Aviation Emissions Inventory Code (AEIC) (Simone, Stettler, Eastham, & Barrett, 2013; Olsen, Weubbles, & Owen, 2013), daily biomass burning emissions from GFEDv4 obtained using the GFED3 daily fractions (years after 2014 use recycled 2014 estimates) (Giglio, Randerson, & van der Werf, 2013), three hourly SiB3 balanced biosphere fluxes (years after 2010 are recycling 2010 estimates) (Messerschmidt et al., 2013) with annual net biosphere exchange based on TransCom from 2000 (Baker et al., 2006), and scaled ocean exchange from Takahashi et al. (2009) (years after 2013 are recycling 2013 estimates). The emissions inventories are plotted in Figure 4. For comparison with the GOSAT and OCO-2 XCO₂, the offset due to the initial conditions chosen for the run was corrected by matching the model average and GOSAT-measured XCO₂.

Development of a New TCCON FTS Container with LIDAR Capability

The container (L: 7060 mm, W: 2280 mm, H: 2470 mm), houses a high-resolution (HR) Fourier-transform infrared spectrometer (FTS), model Bruker 125HR (Bruker Optics Corp., Billerica MA, USA) with a maximum spectral resolution of 0.0035 cm⁻¹. This instrument is the heart of every TCCON station. A solar tracker with a CamTracker® function ensures precise and accurate tracking of the solar disc to within ± 0.1°. Two types of beam splitters enable measurements in the near infrared (NIR) region (around 670 nm to 2000 nm) and in the mid-infrared (MIR) region

(around 2000 nm to 13,500 nm). In addition to TCCON measurements in the NIR, MIR measurements will enable retrieval of altitude-profile information of several atmospheric pollutants, e.g., carbon monoxide (CO), hydrogen cyanide (HCN), ozone (O₃), and others. Four detectors will be used: silicon (Si) and indium gallium arsenide (InGaAs) for TCCON mode; indium antimonide (InSb) and mercury cadmium telluride (HgCdTe) for the MIR (plus the necessary optical filters). The station is also equipped with hydrobromic acid (HBr) and hydrochloric acid (HCl) cells for regular determination of instrument alignment. During the early stages, remote-controlled manual operation (via internet) with on-site support is planned, followed by automatic operation later, which builds upon previous automated TCCON operation experience. Also in the container is a LiDAR (Light Detection and Ranging) system capable of measuring water vapor, aerosol, and cirrus cloud profiles up to the stratosphere. It operates at two wavelengths: 1064 nm and 532 nm with two polarization channels.

A weather station, following TCCON data protocol, will measure temperature and humidity inside and outside of the container as well as wind speed and wind direction. A pyranometer will be used to measure solar radiation.

The following will be installed later: a sky radiometer, an all-sky camera (Skyview), a photometer for aerosol optical depth, and cloud measurements, as well as a liquid nitrogen (LN2) generator (for InSb and HgCdTe detector cooling).

Results and Discussions

XCO₂ Over Burgos

Figure 3b shows the time series of the daily mean XCO₂ within a 400-km radius centered in Burgos, measured from GOSAT and OCO-2. A clear seasonal cycle with a maximum around April and a minimum around October can be seen, especially during the later years when OCO-2 measurements were possible. GOSAT can measure 750 km across in one swath, leading to more regional data. However due to the pixel size of GOSAT (10 km across), cloudy skies especially in the rainy season lead to fewer data. OCO-2 has a narrow swath (10.6 km), but its smaller pixels (1.29 km × 2.25 km) may be able to “see through” clear patches amid cloudy skies, leading to more local data. Figure 3b shows the complementary nature of these two instruments.

Clear Sky Probabilities

The MODIS clear sky statistics from the different candidate sites, which were originally considered for the SE Asia TCCON station, are listed in Table 1. Figure 5 shows the clear sky probabilities calculated from the GOSAT CAI.

Figure 4. Year specific annual emissions used for the CO_2 simulations: (a) aviation emissions (fuel burn) summed vertically from 2005, (b) biofuel emissions from 1995, (c) biomass burning from 2014, (d) fossil fuel emissions from 2014, (e) net terrestrial exchange from 2000, (f) shipping emissions from 2004, (g) ocean exchange based on 2013, and (h) balanced biosphere fluxes from 2010.

The two other candidate sites in the Philippines (Leyte and Negros), both strategically located near the western Pacific warm pool, are also ready for a TCCON station. However, for satellite validation and for maximizing measurements over clear skies, Burgos stands out with the frequency of clear sky opportunities and being located in a prominent clear patch, as shown in Figure 5.

Measurement Sensitivity to Surface Fluxes

Table 1. MODIS Clear Pixels at $0.1^\circ \times 0.1^\circ$ (in %)

Site	Oct '12	Jan '13	Apr '13	Jul '13	Average
Burgos	58.6	69.0	59.0	11.3	49.5
Leyte	10.7	8.3	20.6	5.7	11.3
Negros	9.3	9.3	33.2	11.0	15.7
Phimai	47.3	48.1	7.2	0.0	25.6
Katotabang	1.2	1.0	2.9	24.3	7.4

Figure 5. Clear sky probabilities calculated from each pixel (color-coded) measured by the GOSAT Cloud and Aerosol Imager (CAI). The pixel sizes are approximately 500 m x 500 m. The numbers in % over the assessed sites: Burgos, Leyte, and Negros (including two other sites Phimai in Thailand and Kototabang Indonesia), indicate the probability that the closest pixel has a value of “1” (clear) out of 120 overpasses for 2014.

Figure 6 shows that the Burgos site covers the short-term footprint of the Tropical Western Pacific. Depending on the season, the footprints also include Taiwan, Hong Kong, and parts of Eastern and Southeastern China. The spatial distribution and variability of the surface emissions around this region can be inferred from Figure 4. This demonstrates that the location of this future TCCON site will measure air with significant and variable contributions from emissions of some of the largest anthropogenic carbon sources in the world.

Model Comparison Results

The modeled XCO_2 over Burgos calculated by GEOS-Chem is shown in Figure 7, zoomed in around 2014-2016 (black line). XCO_2 data from GOSAT (cyan circles) and OCO-2 (magenta squares) are superimposed. Table 2 shows the satellite-derived XCO_2 and GEOS-chem XCO_2 differences. The model shows a closer agreement to GOSAT XCO_2 . The reason for this result is that the GEOS-Chem offset due to the initial conditions was optimized to the GOSAT-measured XCO_2 . Nevertheless, data from the model and from the two satellites capture the seasonal cycle. There is a slight drift during the later years where the model shows less XCO_2 . This is due to the 2014 fossil fuel fluxes that were recycled for 2015 to 2016, resulting in an underestimate of fossil fuel flux, and hence the CO_2 growth rate, during these years. This shows how sensitive the XCO_2 measurements are to real-world fossil fuel emissions.

Table 2. Satellite and GEOS Chem XCO_2 differences.

Months	GOSAT-Model		OCO ₂ -Model	
	ΔXCO_2 (ppm)	StDev (ppm)	ΔXCO_2 (ppm)	StDev (ppm)
SON	0.0403	0.1970	0.0806	0.2727
DJF	0.0221	0.1474	0.1033	0.3049
MAM	0.0580	0.2341	0.0833	0.2769
JJA	0.0290	0.1681	0.0543	0.2271

Performance of the 125HR: Side-by-Side Comparison with the Tsukuba TCCON FTS, Alignment, and Line Shape

A side-by-side comparison of Xgas measurements against the established TCCON station in Tsukuba, Japan (Ohya et al., 2009) was performed on the 31st of March 2015. TCCON protocols were followed for the measurements and data processing. Table 3 shows very good agreements between the Xgas amounts from both instruments. The differences are well within the accepted error budget of TCCON. Figure 8 shows a characterization of the instrument performance. The top left panel shows the modulation efficiency of the spectrometer measured using an HCl gas cell (Hase et al., 2013). This measurement procedure yields a value of about 96.5% at 45 cm OPD (optical path difference). It should be noted that an earthquake slightly affected the alignment, which could have caused the modulation efficiency to decrease from an ideal value of 100%. However, this is still in the range specified in Hase et al. (2013) and Griffith (2010). Re-alignment will be necessary upon installation in Burgos.

Figure 6. These panels show the sensitivity (color-coded) of the column measurements in Burgos with respect to the surrounding surface fluxes. The distribution of the sensitivity of CO₂ concentrations with respect to the concentrations in adjacent cells are expressed in ppm/(μmol/m² s). Values are calculated using the FLEXPART model with a resolution of 1.0° for the Burgos site.

Figure 7. XCO₂ over Burgos derived from GOSAT, OCO-2, and the GEOS Chem model.

Figure 8. (a) Modulation efficiency as a function of the OPD, (b) phase error as a function of OPD, and (c) instrument line shape (ILS).

Table 3. Side-by-side comparison of Xgas measurements between Tsukuba TCCON and NIES container FTS for Burgos on March 31, 2015 at 14:42 local time.

	Container FTS for Burgos	Tsukuba TCCON FTS	Differences
XCO ₂ (ppm)	402.58 ± 0.51	402.84 ± 0.30	-0.26 (-0.032%)
XCH ₄ (ppm)	1.821 ± 0.002	1.823 ± 0.001	-0.002 (-0.055%)
XCO (ppb)	106.2 ± 0.2	107.0 ± 0.3	-0.8 (-0.38%)
XN ₂ O (ppb)	317.73 ± 0.85	320.03 ± 0.47	-2.3 (-0.36%)
XH ₂ O (ppm)	1853.2 ± 14.7	1851.1 ± 14.2	2.1 (0.056%)
XHF (ppt)	56.8 ± 0.1	56.6 ± 0.9	0.2 (0.18%)

Conclusions

This study showed an assessment of the future TCCON site in the Philippines. The study inferred from GOSAT data that the chosen site in Burgos is in a region with a prominent clear-sky patch, exceeding the calculated clear-sky probabilities of four other candidate sites in SE Asia. This condition is desirable both for satellite validation and for maximizing TCCON observations. The total column measurement sensitivity to surface fluxes at the TCCON site in Burgos was calculated to show the spatial

coverage of future measurements. GEOS-Chem modeling of the XCO₂ at the site was also done and compared with actual measurements of GOSAT and OCO-2. Satellite measurements and model simulations agree qualitatively on the seasonal variability, however the future TCCON measurements are expected to fill in important data gaps. The NIES TCCON instrument for Burgos has been tested, characterized, and compared with the established TCCON station in Tsukuba, Japan. The results of the comparison show very small differences in the retrieved total column values of several trace gases. The measurement difference in XCO₂ is well within the error budget of TCCON. The instrument arrived in Burgos, Ilocos Norte, Philippines and installation was finished last February 2017. Full operations are expected to commence by April 2017, allowing ample time for measurements before the launch of GOSAT-2.

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