GRUAN OZONESONDE TECHNICAL DOCUMENT

Jacquelyn C. Witte[1,2], Greg E. Bodeker[3], Richard Querel[4], and Anne M. Thompson[2]

[1]Science Systems and Applications Inc., [2]NASA/Goddard Space Flight Center, [3]Bodeker Scientific, [4]National Institute for Water and Atmospheric Research

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Purpose of this Guide

This Document of GCOS Reference Upper Air Network (GRUAN) ozonesonde operations provides both mandatory operating protocols and non-mandatory recommendations for measurements of vertical ozone profiles using ozonesondes within GRUAN. This Document relies on the standard operating protocols, instrument selection, and uncertainty estimates and calculations from the WMO/GAW Report #201 [Smit et al., 2014], Assessment of Standard Operating Procedures for Ozone Sondes (ASOPOS) panel recommendations, and the large body of peer-reviewed literature on ozonesondes. This Document also builds on the GRUAN *Manual* and *Guide to Operations* (herein referred to as GCOS-171). As in the GRUAN Manual and Guide, mandatory operating protocols are distinguished by the words ‘shall’ or ‘must’ while guidelines are distinguished by the words ‘could’ or ‘should’.

The primary goal of GRUAN is to provide vertical profiles of reference measurements suitable for reliably detecting changes in global and regional climate on decadal time scales. GRUAN’s goals have been agreed to by GCOS (Global Climate Observing System) and WMO (World Meteorological Organization). Ozone is classified as a priority 2 essential climate variable (ECV) within GRUAN. GRUAN ozonesonde measurements will provide a traceable reference standard for global satellite-based measurements of atmospheric ozone. GRUAN ozonesonde measurements will also ensure that potential gaps in satellite measurement programmes do not invalidate the long-term ozone record, and will provide data to fully characterize the properties of the atmospheric column. Because ozone is a key radiatively active gas, vertically resolved measurements of the ozone profile are essential for characterizing radiative transfer through the atmospheric column.

From Section 6.1 of GCOS-171:

> “GRUAN will not prescribe the use of specific instruments in the network since the emphasis is not on prescribing an instrument, but rather on prescribing the capabilities required of an instrument and allowing individual sites to select an instrument that achieves those capabilities.”

This GRUAN Ozonesonde Technical Document includes frequent references to the requirements described in the GRUAN *Guide to Operations* (GCOS-171), and provides additional ozonesonde-specific requirements not described in GCOS-171. It defines the requirements on random and systematic uncertainty and long-term stability for the operations of all ozonesonde instruments in use at GRUAN sites. This Document establishes the philosophy under which GRUAN ozonesondes shall operate. It informs current and future GRUAN sites of the expected *modus operandi* for ozonesonde operations at GRUAN sites. The overall framework under which an ozonesonde will operate in GRUAN is hereafter referred to as the 'GRUAN Ozonesonde Programme'.

The GRUAN community is not the international authority on ozonesonde operations. This Document has been developed in close collaboration with international leaders in the development of ozonesonde standard operating procedures (SOP). These are the principles in the WMO ozonesonde community (Dr. H. Smit/Research Centre Jülich GmbH, and collaborators who developed ASOPOS), the Network for Detection of Atmospheric Composition Change (NDACC) working group, and the principles in the Southern Hemisphere ADditional OZonesondes (SHADOZ) network.

Relevant information from this GRUAN Ozonesonde Technical Document is expected to be incorporated into the WMO Manual on the Global Observing System (WMO-No. 544) and the Guide on the Global Observing System (WMO-No. 488). This Guide may be additionally supported by a series of technical documents listed on the GRUAN web site at http://www.gruan.org.

2.1 Table of Contents

1. INTRODUCTION

1.1. Ozonesonde heritage

Ozone is a key trace gas in Earth's atmosphere. In the stratosphere it absorbs incoming solar radiation in the UVC (<280 nm) and UVB (280-320 nm) portions of the spectrum. Because radiation at these wavelengths has sufficiently high energy to be detrimental to biological systems, the stratospheric ozone layer provides an essential screen, thus protecting life on Earth's surface. During the latter half of the 20th century the stratospheric ozone layer was depleted, most severely over Antarctica, due to anthropogenic emissions of ozone depleting substances. As a result of the successful implementation of the Vienna Convention for the Protection of the Ozone Layer and its Montreal Protocol (including amendments and adjustments to the Protocol), emissions of ozone depleting substances have declined dramatically and the status of the ozone layer is expected to return to a mid-20th century state in the second half of the 21st century.

The effects of ozone are not always positive. Ozone is a key component of photochemical smog and high levels of ozone are associated with poor air quality. The common saying is that ozone is 'nice from far but far from nice'. Ozone in the troposphere also acts as a strong oxidizer and this removes many compounds, including toxic substances, from the air. Ozone levels therefore play a role in determining the tropospheric lifetimes of many compounds. Ozone is also a greenhouse gas, absorbing outgoing infrared radiation from Earth's atmosphere. Because of its importance both as an absorber of incoming solar UV radiation, and as an absorber of outgoing infrared radiation, it is essential that changes in ozone concentrations throughout the atmosphere are carefully monitored.

The vertical distribution of ozone in the atmosphere can be monitored using a range of different techniques including satellite-based (solar occultation, limb-sounding, nadir viewing) instruments, balloon-borne *in situ* instruments (ozonesondes, dropsondes), and ground-based remote sensing systems (lidars and microwave radiometers). Ozonesondes fulfil an important role in this suite of techniques by providing very high vertical resolution ozone profiles from the surface to the middle stratosphere (30-35 km) with small measurement uncertainties, capable of making measurements during periods of no sunlight, and can be easily deployed from remote locations such as ships or small islands.

A number of quasi-independent ozonesonde measurement programmes have been established globally to monitor changes in the vertical distribution of ozone. The WMO/GAW[1], NDACC, and SHADOZ communities have established an expert panel, ASOPOS (Assessment of Standard Operating Procedures for Ozonesondes), to develop standard operating procedures for ozonesonde measurement programmes. This Document builds considerably on the large body of material already developed by ASOPOS [Smit et al., 2012].

Because long-term satellite-based measurements of ozone in the troposphere and upper troposphere/lower stratosphere (UTLS) are not currently available, the ozonesonde record provides the primary source for deriving ozone trends in the troposphere and UTLS, especially in the climate sensitive region around the tropopause. When combined with satellite-based

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[1] A complete list of all acronyms appearing in this Document is provided at the end of the document.

measurements of ozone, ozonesondes can provide a global, multi-decadal data set extending from the surface to the mesosphere for long-term ozone trend detection (Bodeker et al., 2012).

There are challenges in making ozonesonde measurements such that they will meet the needs of GRUAN users (see Section 1.2). Most ozonesondes are only flown once, making re-calibration of the hardware impossible. Pre-flight calibration and quality checks of the hardware are essential. Ensuring inter-instrument calibration in an environment where instruments from different manufacturing batches may show systematic biases (Smit et al., 2007), presents a challenge.

1.2. The purpose of ozonesondes within GRUAN

As detailed in GCOS-112, GRUAN's objectives are to:

i) Provide long-term high quality climate records;

ii) Constrain and calibrate data from more spatially-comprehensive global observing systems (including satellites and current radiosonde networks); and

iii) Fully characterize the properties of the atmospheric column.

To achieve these goals with respect to ozone, sites within the network should provide vertical profiles of reference measurements of ozone for reliably detecting changes in global and regional climate, on multi-decadal time scales, for major climatically distinct regions of the globe. Changes in ozone, both in the stratosphere and troposphere are known to drive changes in global and regional climate. Reference within GRUAN means that, at a minimum, the observations are tied to a traceable standard, that the uncertainty of the measurement has been determined, and that the entire measurement procedure and set of processing algorithms are properly documented and accessible (Immler et al., 2010).

Potential uses of such ozonesonde measurements include:

i) Providing measurements at GRUAN sites that complement the priority 1 measurements of temperature, pressure and water vapour and priority 2 measurements of ozone. Understanding changes in the vertical distribution of ozone is required to understand changes in the vertical distribution of temperature.

ii) Providing high-resolution profile measurements of ozone that are not possible with current satellite-based measurements.

The four key user groups of GRUAN ozonesonde ozone profiles are the same as those identified in the GRUAN *Guide to Operations*, viz.:

i) The climate detection and attribution community. Understanding changes in the vertical distribution of ozone is essential to understanding changes in the thermal structure of the atmospheric column.

ii) The satellite community. Validating satellite-based measurements of ozone is recognized as an essential requirement of the GRUAN ozonesonde programme.

iii) The atmospheric process studies community. High vertical resolution measurements of the ozone profile, with well-resolved measurement uncertainties, provide key data for understanding atmospheric processes. Many aspects of stratospheric dynamics and the dynamics associated with stratosphere-troposphere exchange can be studied using ozone profiles from ozonesondes. Ozonesonde measurements have played a key role in determining ozone loss rates in the Arctic vortex (Rex et al., 1998).

iv) The numerical weather prediction (NWP) community.

1.3. Organization and design of the GRUAN Ozonesonde Programme

GRUAN operates under the joint governance of GCOS and WMO as a WIGOS Implementation Project. A defining attribute of GRUAN is the standardization and centralization of data processing with the goal of ensuring network-wide homogeneity of the resultant data products.

1.3.1. Terminology

A GRUAN Ozonesonde Programme is an ozonesonde measurement programme implemented at a site and having been assessed and certified as defined in Sections 4.1 and 4.2.

A *GRUAN Ozonesonde instrument* is one of the instruments employed in a GRUAN ozonesonde programme. These are balloon-borne electrochemical concentration cell (ECC) ozone sensors that measure high vertical resolution profiles of ozone, pressure, temperature, and relative humidity. ECC ozone sensors are described in Section 2.1

A *GRUAN Ozonesonde Product* is an ozone product resulting from the measurements made within a GRUAN ozonesonde programme. A GRUAN Ozonesonde Product is always produced by the GRUAN Ozonesonde Analysis Software System (GOASS, see Section 4.7) designed to implement the requirements and recommendations defined in this document.

1.3.2. Responsibilities

The GRUAN Task Team on Radiosondes (TTR), in consultation with the GRUAN Lead Centre and Task Team on Ancillary Measurements, is responsible for integrating best ozonesonde measurement practices into GRUAN operations. These best practices shall be synthesized in the form of requirements and recommendations compiled in this Document and shall be implemented in all certified GRUAN Ozonesonde Programmes.

GRUAN sites hosting a GRUAN Ozonesonde Programme shall use a designated system of methods, techniques and facilities in full compliance with the requirements and recommendations detailed in this document. For any given GRUAN Ozonesonde Programme, this system will not be changed without advanced notice to the TTR and GRUAN Lead Centre. GRUAN Ozonesonde Programmes incorporate a programme to validate the stability and uncertainty of the measurements, agreed with WG-GRUAN, and managed in detail by the GRUAN TTR and GRUAN Lead Centre. This assurance programme comprises three mandatory components, which are the GRUAN *Standard Operating Procedures* (SOP) for all GRUAN ozonesonde instrument calibration (described in Section 4.5), the RSLaunchClient (described in Section 4.6), and the GOASS (described in Section 4.7).

The design of GRUAN Ozonesonde Programmes shall recognize the heterogeneity of the network of sites, many of which will have primary responsibility to networks other than

GRUAN. GRUAN Ozonesonde Programmes shall integrate, where possible and when feasible, with other international long-term monitoring programmes.

GRUAN Ozonesonde Programmes shall be responsive to the latest technological and scientific progress in ozonesonde measurement techniques and observational requirements. Non-GRUAN ozonesonde development work can continue at a GRUAN site in collaboration with the TTR until mature and validated, at which point any improvements can be introduced into GRUAN operations with the agreement of the TTR and GRUAN Lean Centre.

WG-GRUAN, the GRUAN Lead Centre and TTR will act as the interfaces between GRUAN and the community of users of GRUAN ozonesonde products.

1.4. Implementation of GRUAN Ozonesonde Programmes

The implementation of the GRUAN Ozonesonde Programmes, as a whole, and specific issues relevant to an individual Ozonesonde Programme shall be guided by the TTR and WG-GRUAN. These two teams will work with other relevant expertise in support of GRUAN and coordinate with the GRUAN Lead Centre.

The WG-GRUAN and TTR shall use this Document which establishes standard operational procedures (SOP) and metadata requirements for all GRUAN Ozonesonde Programmes. The TTR shall evaluate the appropriateness of uncertainty estimates, the usefulness of particular measurements and operational procedures, synthesize the available knowledge, and develop recommendations to improve GRUAN measurements and operations. The TTR and WG-GRUAN shall confer regularly to evaluate the current status of GRUAN observations, to identify weaknesses, and to incorporate new scientific understanding into GRUAN. The expertise of these teams shall also be used to support the Lead Centre in guiding individual sites through changes in instrumentation and operating procedures without impacting long-term measurement time series.

The GRUAN Lead Centre shall identify sites where instrument operators need training, re-training, and organise cost-efficient training courses for the network at appropriate locations, as advised by the appropriate TTR, to encourage uniformity of instrument operation between sites. The Lead Centre may liaise with National Metrological Institutes in this regard.

All activities associated with the implementation of GRUAN are the responsibility of the institution/organization hosting the GRUAN site and should, as far as possible, be met through national funding. To best serve the needs of the climate monitoring and research communities, it is essential that GRUAN is cognizant of the evolving science that drives the measurements and accuracy of the GRUAN data. The ozonesonde instrumentation deployed and the observing schedules may differ among sites, as agreed with WG-GRUAN as part of the site assessment and certification process, but the practices are expected to be uniform among all GRUAN sites.

1.5. Links to partner networks and satellite-based measurement programmes

In the original charter for GRUAN (GCOS-92) it is stated that 'where feasible, the GRUAN sites should be co-located and consolidated with other climate monitoring instrumentation'. GRUAN Ozonesonde Programmes shall not be run in isolation of existing ozonesonde networks and GRUAN is not intended to replace existing networks. GRUAN Ozonesonde Programmes are likely to operate within the framework of existing networks such as the Network for the Detection of Atmospheric Composition Change (NDACC) and SHADOZ (Southern Hemisphere ADditional OZonesondes), and to leverage off the expertise available in these networks and e.g. through the GAW (Global Atmosphere Watch[2]) scientific advisory group for ozone. As a result, close and regular coordination between the governing bodies of these networks and with the WG-GRUAN and GRUAN TTR+AM is required. This coordination can be achieved by having members of the WG-GRUAN and TTR+AM attend steering group meetings of partner networks and by inviting co-chairs or steering group members from partner networks to attend WG-GRUAN and GRUAN TTR+AM meetings.

1.5.1. NDACC (Network for the Detection of Atmospheric Composition Change)

NDACC comprises more than 70 remote-sensing research sites for observing and understanding the physical and chemical state of the stratosphere and upper troposphere and for assessing the impact of stratospheric changes on the underlying troposphere and on global climate. A number of NDACC sites fly ozonesondes and NDACC has a standing Sonde Working Group on ozonesondes, water vapor sondes, and aerosol sondes.

1.5.2. GAW (Global Atmosphere Watch)

GAW is a coordinated network of observing stations, associated facilities, and related scientific assessment activities that supply basic information to be used by policy-makers [Global Atmosphere Watch Guide, GAW Report No.86, 1993]. GAW does not provide or archive observations, but serves an important link between end users and high quality data networks that include world data centres, such as the WOUDC (World Ozone Ultraviolet Data Centre) and other archives, such as SHADOZ.

1.5.3. Atmospheric Radiation Measurement (ARM) Programme

The goal of the U.S. Department of Energy ARM programme is to study changes in climate, land productivity, oceans or other water resources, atmospheric chemistry, and ecological systems that may alter the capacity of the Earth to sustain life. This includes improving the atmospheric data sets used in regional and global climate models. A primary objective of the ARM user facility is to improve scientific understanding of the fundamental physics related to interactions between clouds and radiative processes in the atmosphere.

A dedicated Data Quality (DQ) Office provides ARM with a number of tools to ensure the high quality of the collected data. The potential use of these tools in GRUAN must be explored to ensure network-wide homogeneity of the GRUAN ozonesonde measurements. The ARM DQ

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[2] http://www.wmo.ch/web/arep/gaw/gaw_home.html

Office has developed a suite of sophisticated data quality visualization tools that may be of interest to GRUAN Ozonesonde Programmes.

1.5.4. SHADOZ (Southern Hemisphere ADditional OZonesondes)

SHADOZ (Southern Hemisphere ADditional OZonesonde) is a project to augment and archive ozonesonde data from over a dozen tropical and sub-tropical sites and has become the central repository for vertical profiles of ozone in the tropics/sub-tropics. Prior to the creation of SHADOZ, tropical ozonesonde data were accessible via campaigns or collaborative associations with specific operating site representatives. Started in 1998 by NASA's Goddard Space Flight Center, and other US and international co-investigators, SHADOZ is an important tool for equatorial tropospheric ozone research. The rationale for SHADOZ is to: (1) validate and improve model and remote sensing techniques for estimating tropical ozone, (2) contribute to climatology and trend analyses of tropical ozone and (3) provide research topics to scientists and educate students, especially in participating countries [Thompson et al., 2003a; 2003b, 2004, 2007, 2012]. SHADOZ functions as a data service to the global scientific community by providing a central public archive location via the internet: http://tropo.gsfc.nasa.gov/shadoz. SHADOZ data are mirrored at the Aura Validation Data Center (AVDC) and are deposited to WOUDC. While the SHADOZ website maintains a standard data format for the archive, it also informs data users of the differing sites' preparation techniques and data treatment. Data from launches from various related field campaigns, such as, the Indian Ocean Experiment (INDOEX), Sounding of Ozone and Water in the Equatorial Region (SOWER) and Aerosols99 Atlantic Cruise are also available.

1.5.5. Satellite-based measurement programmes

Ozonesonde measurements have historically provided a key data set for validating satellite-based measurements of ozone. GRUAN Ozonesonde Programmes, with their well-characterized measurement uncertainties and network wide homogeneity are expected to provide a database of vertically resolved ozone that will be essential for validating satellite-based measurements of the vertical distribution of ozone. Because the GRUAN ozonesonde measurements are likely to serve a wide range of end-users within the satellite measurement community, WG-GRUAN and TTR+AM members shall be assigned to liaise with key clients within the satellite community to ensure that GRUAN ozonesonde data products are tailored, where possible, to best meet the needs of this community. Once GRUAN ozonesonde data sets are available, pilot studies on enhanced combined data sets using these reference measurements e.g. generating site atmospheric state best estimates (SASBEs) for ozone, need to be undertaken. The GRUAN ozonesonde measurements provide an essential database for correcting offsets and drifts between separate satellite-based measurement series within the limitations imposed by the uncertainties on the GRUAN ozonesonde measurements.

2. GRUAN OZONESONDE TECHNIQUES AND MEASUREMENT PRINCIPLES

This section provides the GRUAN Ozonesonde Programmes and user community with essential knowledge of the way ozonesondes measure profiles of ozone. For further comprehensive reviews of the ozonesonde measurement technique, the reader should refer to the publications mentioned in this section.

Ozonesondes are small, lightweight balloon-borne instruments that use an electro-chemical technique to make in situ measurements of ozone from the surface of the Earth to an altitude determined by balloon burst, typically 30 to 35 km [Smit et al., 2002]. The ozonesonde is interfaced to a standard meteorological radiosonde for transmission of the data to the ground and is usually flown together with the radiosonde as part of the same package. The package is carried aloft by a rubber balloon similar to that used for radiosonde measurements, though in this case a 1000-1500 g balloon is typically used rather than the standard 300 g meteorological balloon. The package ascends through the atmosphere at ~5-7 $m.s^{-1}$ and, with a measurement frequency of ~1 second, results in a vertical measurement resolution of less than 10 m (however, sensor time-constants expand this, typically by a factor of 10). Ozonesondes constitute the most important data source with long term-data coverage for the derivation of ozone trends with sufficient vertical resolution, particularly in the important, climate sensitive, altitude region around the tropopause.

As defined in GCOS-171:

"A reference measurement result typically arises from a defined measurement procedure that involves standards traceable to national or international standards as maintained at National Metrological Institutes (NMIs). For GRUAN, a reference measurement is one where the uncertainty of the calibration and the measurement itself is carefully assessed. This includes the requirement that all known biases have been identified and corrected, and, furthermore, that the uncertainty on these bias corrections has also been determined and reported. An additional requirement for a reference measurement is that the measurement method and associated uncertainties should be accepted by the user community as being appropriate for the application."

To produce GRUAN ozonesonde reference measurements, mandatory and recommended processing procedures have been established such that the ozonesonde data products derived shall be reproducible at any time in the future. Section 2 describes the data processing procedures required for each component of the ozonesonde measurement technique. The GRUAN Ozonesonde Programmes and centralized ozonesonde data processing facility shall apply these procedures to create the standard reference GRUAN ozonesonde data product (see Sections 4.5 - 4.7).

As of the time of the development of this Technical Document, the Electrochemical Concentration Cell (ECC) sonde (Komhyr, 1969) is the dominant type of ozonesonde being flown world-wide and therefore this document focusses solely on SOP for the ECC sonde type. Brewer-Mast (BM) type sondes (Brewer and Milford, 1960) are flown operationally only at the Hohenpeissenberg, Germany station. ECCs have replaced the Japanese manufactured Carbon

Iodide (CI) sonde (Kobayashi and Toyama, 1966). Little is known about the Indian-sondes which are flown exclusively in India. The homogenization of time series that have used BM and ECC sondes at the Uccle, Belgium, site has been first undertaken by De Backer [1999] using results from dual BM/ECC sonde launches [De Backer et al., 1998], then recently by Van Malderen et al. [2016] – see also Section 7.2 on the use of transfer functions for homogenizing time series that include BM and ECC sondes. Dual flight campaigns at the Payerne, Switzerland, site showed no detectable differences between their BM and ECC sondes [Stübi et al., 2008]. Since the late 2000s, Japanese sites have switched from using CI sondes to using ECC sondes. Although Nakamura et al. [2008] conducted inter-comparison studies for CI and ECC sondes, transfer functions between the two sensors have not yet been derived.

2.1. The ozonesonde measurement

The ECC instrument consists of a non-reactive teflon gas-sampling pump connected to an ECC ozone sensor, and an electronic interface that connects the ozone sensor to a radiosonde for data telemetry (see Figure 1 of Komhyr, 1995). The instrument is encased in a polystyrene weatherproof box during flight to insulate and prevent the sensing solutions from freezing. Measurements of ozone partial pressure, the sonde's pump temperature, motor voltage and current, air temperature, air pressure and humidity are transmitted to a ground receiving station. Winds derived from GPS/GNSS-enabled measurements became available in the early 2000s.

The ECC sensor measures ozone using iodine/iodide electrode reactions [Vetter, 1967]. Two platinum electrodes are immersed in separate cathode and anode chambers made of Teflon, also called half cells, of differing concentrations of potassium iodide (KI) solution. The anode cell contains a solution saturated with KI. Both cells contain an equal concentration of potassium bromide (KBr) and a phosphate buffer to maintain a neutral pH. An ion bridge connecting the two chambers allows ions to flow between the two cells but prevents mixing, thereby preserving their respective concentrations.

Ambient air containing ozone (O_3) is pumped into the cathode cell and reacts with iodide (I^-) to form iodine (I_2) based on the aqueous reaction:

$$2KI + O_3 + H_2O \Rightarrow I_2 + O_2 + 2KOH \qquad \text{Rxn. 1}$$

To maintain electrochemical equilibrium iodine is converted back to iodide on the platinum electrode resulting in the release of two electrons by the following reactions:

In the cathode cell: $3I^- \Rightarrow I_3^- + 2e$ Rxn 2

In the anode cell: $I_2 + 2e \Rightarrow 2\,I^-$ Rxn. 3

The total cell reaction is the redox reaction: $3I^- + I_2 \Rightarrow I_3^- + 2I^-$ Rxn. 4

Rxn 2 and 3 are rate determining reactions and result in the transfer of ion to the electrode surfaces. An equilibrium exists between I_2 and I_3^- (tri-iodide) when the concentrations of I^- are kept constant.

As a result of the reactions detailed above, each ozone molecule entering the sensor causes two electrons to flow through the ECC's external circuit, which are measured as a current. The resulting electrical current is linearly proportional to the concentration of ozone in the sampled air. The electrochemical technique assumes no secondary reactions take place and a 1:1 stoichiometric relationship of the I_2:O_3 ratio is maintained. The relationship between ozone and the electrical current (measured in μA) is computed using:

$$P_{O3} = 4.307\times10^{-4}\,(I_M - I_{BG})T_P\Phi_{Ground}\psi \qquad \text{Eqn. 1}$$

where,

P_{O3} = Ozone partial pressure (mPa)
I_M = Cell current (μA)
I_{BG} = Cell background current (μA)
T_P = Ozonesonde pump temperature (K)
Φ_{Ground} = Pump flow rate at the ground (s/100cm^{-3})
ψ= Pump flow conversion efficiency (1/pump flow correction factor, unitless)

The constant, 4.307×10^{-4}, is the half ratio of the ideal gas constant to Faraday's constant. Measurement techniques and uncertainty estimates for each variable in Eqn. 1 are reviewed below. The cell current, I_M, and pump temperature, T_p, are in situ measurements while the cell background current, I_B, and flow rate, Φ_{Ground}, are measured during pre-flight preparations under ambient laboratory conditions and are assumed to remain constant throughout the flight. While it is preferable that the conversion efficiency, ψ, be determined for each flight, unless automated, this can be very time consuming and as a result ψ values are usually taken from a table of pump flow measurements made at varying low pressures to account for the decrease in pump efficiency at low pressures. Uncertainties on ψ are expected to be smaller if they are determined individually for each flight rather than taken from a table (which needs to also provide the statistical uncertainty on the ψ values). ψ values vary with ECC sensor type and are further explained in Section 2.5.

2.2. Measuring the background current

The background current (I_B) is the residual current measured by the sonde when sampling ozone-free air. Conventional processing of the sonde telemetry assumes that the background current remains constant during flight and the same assumption is made when processing ozonesonde data within GRUAN. As seen in Equation 1, the background current is subtracted from the ECC sensor current to infer the ozone partial pressure. In the initial conditioning procedure, both cathode and anode cells are filled with sensing solution and stored for no less than 3 days prior to launch to reduce the background current and improve the sensor response time (i.e. the time it takes for the sensor electronics to respond to a change in ozone concentration) [Kohmyr, 1986; 1997]. Kohmyr and Harris [1971] show that the background current decreases after the ECC is stored for several days while charged with their working solutions; they call this process 'self-cleaning'.

GRUAN protocols for measuring background current

GRUAN follows the WMO/GAW SOP for background current measurement [Smit et al. 2014] requiring three background measurements as detailed below.

- Initial conditioning, i.e. the conditioning procedures when the sensor is first taken out of the box, shall occur no less than 3 days before the ozonesonde flight because this is the minimum acceptable period for the background current to decrease to within the thresholds defined below.

- Day of flight preparations shall be made no more than 7 days after the initial conditioning. If more than 7 days have elapsed, then the cathode and anode chambers should be replaced with fresh solution and a repeat of the response time test steps should be done.

- I_{B0} is recorded when the calibration/ozonizer unit is used to run ozone-free air through the sensor, filled with fresh solution, after 10 minutes.
    - Following BESOS procedures [Deshler et al, 2008] ozone-free air is run through the sensor until the background no longer drops or until the background current is less than 0.05 µA.
    - If the background current does not drop below 0.05 µA after 20 minutes, the solutions must be changed and the background current measurement repeated. If, after another 20 minutes, the background does not fall below 0.05 µA the final value should be recorded in the metadata check list, regardless. Ideally, these steps should bring I_{B0} below the 0.05 µA threshold value.

- I_{B1} is recorded after the response time measurement, i.e. the time required for the sensor current to drop from 4 µA to 1.5 µA, and after an additional 10 minutes of ozone-free air has been pumped into the cathode cell. This value may be higher than I_{B0}.

- I_{B2} is recorded prior to launch with the ozonesonde intake tube receiving ozone-free air from the ozoniser or ozone destruction filter. This value may be higher than I_{B0}.

All three background currents shall be recorded by the GRUAN RSLaunchClient (see Section 3.6). Historically, operators have used I_{B2} as the value for I_B in Eqn. 1. In recent years other methods of applying background currents have been employed, such as the minimum of the three background currents [Ryan Stauffer/Penn State, personal communication], a laboratory determined I_B [Holger Vömel/NCAR, personal communication], or I_B set to an upper limit value for those background currents that exceed a maximum threshold based on average I_B measured under optimal laboratory conditions [Bryan Johnson/NOAA, personal communication].

For the GRUAN central processing of ozonesonde flight data, operators should specify which final I_B has been applied.

For stations that have on-going issues recording $I_{B2} < 0.05$ µA, GRUAN recommends using I_{B0} as the final background current for the following reasons:

- The quality of the ozone destruction filter under launch conditions (non-laboratory controlled environment) used to measure I_{B2} cannot be assured to be uniform between flights which introduces a source of random uncertainty which cannot be easily quantified [Reid et al., 1996]. This is particularly the case when ozonesondes are flown in the tropics where high humidity affects the ozone removal efficiency of the filter [Newton et al., 2016].

- The use of I_{B2} as the background current is likely an overestimate of the true background current which then leads to an underestimate of the ozone partial pressure. In particular, tropical and polar ozone profiles are strongly influenced by the magnitude of the background current [Reid et al, 1996; Vömel and Diaz, 2010; Newton et al.; 2016]. Under mid-latitude and tropical conditions, Smit et al. [2014] show that background currents ranging from 0.05 to 0.1 μA contribute 10-20% and 20-40%, respectively, to the measured cell current in the free troposphere.
- I_{B1} is excluded as an option since it can be biased high. The 10-minute flow of ozone-free air after ozone exposure is arbitrary and likely not representative of the true background current [Thornton and Niazy, 1982; Vömel and Diaz, 2010; Bryan Johnson/NOAA, personal communication]. Laboratory experiments by Vömel and Diaz [2010] identified the decay of the cell current after exposure to ozone and showed that the current does not relax to pre-ozone values after 10 minutes of ozone-free air and that a much longer period of time (hours) is required to approach initial values. The BESOS field campaign [Deshler et al, 2008] found similar enhancements in the background current after ozone exposure. The elevated cell currents indicate a slower decay in the sensor response suggesting that the flushing of ozone-free air for 10 minutes through the cells is not long enough to reduce the cell current to pre-ozone exposure values.
- A field study conducted by Newton et al. [2016] found stable low background currents when the ozone exposure test during the day of flight preparations was ignored.

Using I_{B0} ensures that background currents are measured under stable, controlled laboratory conditions where uncertainties can be more robustly quantified.

When I_{B0} exceeds 0.05 μA the following steps shall be taken:

1. If a solution change, followed by a reasonable length of time running zero ozone air does not bring I_{B0} below 0.05 μA, then the minimum of I_{B0}, I_{B1}, and I_{B2} shall be used as I_B.
2. If the minimum background current is still greater than 0.05 μA, then the profile data shall not be accepted and zero-air from the ozonizer and destruct filter should be checked and possibly replaced.

GRUAN will apply a constant background current correction following WMO/ASOPOS guidelines [Smit et al. 2012; 2014]. Thornton and Niazy [1982] showed that sensors in the early 1980s exhibited negligible sensitivity to O_2 allowing the background current to be treated as a constant. More recent studies support this finding [Smit et al, 1994; Reid et al. 1996; Newton et al., 2016]. Vömel and Diaz, [2010] introduced a modified ozone partial pressure equation that takes into account the excess ozone response due to the buffering of the solution. They measured uncertainties of 0.005 μA for a 1% full buffer solution and 0.009 μA for a 0.5% half buffered solution.

Any changes to the treatment of ozonesonde background currents to those described above must be founded on JOSIE-type experiments, followed by rigorous assessment and peer-reviewed publication.

2.3. Effects of different sensing solutions and ozonesonde type

While the fundamental chemistry and operating mechanics of the ECC sonde have remained largely unchanged, the KI solution concentrations have varied over the past decades in attempts to improve the measurement accuracy and stability. Inter-comparison campaigns and laboratory studies have been conducted to evaluate the ECC sonde performance using different sensing solution recipes with current sensor types [Hilsenrath et al., 1986; Boyd et al., 1998; Johnson et al., 2002; Smit et al., 2007; Deshler et al, 2008]. The JOSIE studies have shown that the precision and accuracy is strongly dependent on the ozonesonde type and solution [Smit et al., 2007]. JOSIE experiments reveal that differences in instrument construction between Science Pump Corporation (SPC) and EN-SCI ECC's significantly impacts the ozonesonde performance.

There are a variety of sensing solution concentrations and pH buffers used in ECC sondes (see Table 2.3.1) The anode solutions are prepared by saturating the cathode solution with KI crystals.

Table 2.3.1

		pH Buffer, g/L	
Sensing Solution Type	KI, g/L	$NaH_2PO_4 \bullet H_2O$	$Na_2HPO_4 \bullet 12H2O$
1.0% KI, full buffer	10	1.25	5.0
0.5% KI, half buffer	5	0.625	2.5
2.0% KI, no buffer*	20	0	0
1.0% KI, 1/10th buffer*	10	0.125	0.5

* Used at some NOAA-supplied ozonesonde stations only.

The 1.0% KI with full pH-buffer is the conventional cathode sensing solution used for the ozonesonde types SPC-4A, -5A, and -6A [Science Pump Corporation manual, 1996]. Until 1996, ENSCI advocated using the 1.0% solution formula but then switched to recommending a 0.5% KI with half pH-buffer sensing solution formula after 1996 [ENSCI Corporation manual, 1996]. Johnson et al. [2002] introduced the 2.0% non-pH-buffered solution with no KBr that all NOAA-led ozonesonde stations used for a period of almost 10 years in the late-1990s to mid-2000s. This was followed by a switch to a modified 1.0% KI solution using a 1/10th buffer cathode sensing solution recipe. The 2.0% no-buffer solution formula is no longer recommended. The 1.0% KI with 1/10th buffer sensing solution is a relatively new formula and has yet to be included in JOSIE-led evaluation studies. Thus, until the latter solution is fully evaluated, only the 0.5% half buffer and 1.0% full buffer sensing solutions shall be used in GRUAN, following WMO/GAW recommendations and as detailed in Table 2.3.2.

Table 2.3.2 Table of ECC sensors and solution pairing.

Manufacturer/Model	**Solution concentration**
SPC 6A	1%, full buffer
ENSCI Z, 2Z	0.5%, half buffer

The JOSIE-2000 experiment focused on combinations of ECC sensors and sensing solution types to determine the optimal pairing when compared with the calibration standard UV-photometer. Results show a reduction in biases for SPC sondes when using the 1.0% KI solution with full buffer pair and for ENSCI sondes that use a 0.5% KI solution with half buffer solution. JOSIE results showed that the SPC/1.0% and ENSCI/0.5% pairings behave similarly, i.e. measurement differences are within 1.0%.

Homogenizing records that use different sensing solutions

GRUAN recognizes that ECC sensor technology is constantly evolving as solution recipes are fine-tuned to optimize performance and that not all sites coming into GRUAN will operate with the same ECC sensor/solution pairing detailed in Table 2.3.2, e.g. an existing site may continue to use an obsolete sensing solution (e.g. 2% unbuffered) to avoid potentially introducing a discontinuity in the measurement time series, especially if transfer functions have not yet been tested and established.

Ideally, the candidate site should have a legacy of using one of the two combinations defined in Table 2.3.2. Sites using an ECC sensor/solution type outside of the SPC/1.0% or ENSCI/0.5% pairing should be homogenized with the application of transfer functions (see Section 7.2). Systematic biases between ozone measurements typically result from ECC sensors of the same manufacturing type being operated with different sensing solution concentrations. For ozonesonde sites performing long-term measurements, a change of the sensing solution concentration or ECC-sensor type can introduce a ±5% change, or more, in their ozone records, affecting the determination of ozone trends [Smit et al., 2014].

To support the homogenization of ozonesonde measurement series whose homogeneity is compromised by historical changes in sensing solutions, the ASOPOS working group, as part of the SPARC/IGACO-O3/IOC/NDACC (see Acronyms) initiative, has established transfer functions based on JOSIE experiments [Smit et al., 2007] for a variety of ECC sensor type and solution strength combinations. Their use allows homogenization of long-term records to conform to either an SPC/1.0% or ENSCI/0.5% sensor/solution pairing (Refer to Section 8.1.2, Table 3 of Smit et al. [O3S-DQA, 2012] for conversion factors). Section 7.2 provides further details and processing protocols involving transfer functions. Deshler et al. [2017] provides a detailed description on the derivation of the transfer functions for the standard pairings, i.e. SPC/1.0%, ENSCI/0.5%.

While GRUAN Ozonesonde Programmes should commit to using the same ECC sensor and solution type for the lifetime of the measurement programme, changes may be considered if:

- Sufficient justification, as determined by the GRUAN Lead Centre and the centralized GRUAN ozonesonde data processing facility, is provided for the proposed change. A balance must be found between GRUAN Ozonesonde Programmes being responsive to the latest technological and scientific progress in ozonesonde measurement techniques and observational requirements, and the importance of avoiding discontinuities in the climate data record.

- A new model is developed or a new manufacturer enters the ECC market that recommends a new sensing solution recipe.
- An existing model is discontinued, forcing transition to a different model.

Changes in ozonesonde working solutions must be managed through an appropriate change management programme whereby the necessary tests, laboratory studies, and dual sonde launch campaigns are conducted to characterize any systematic biases, and their uncertainties, in the stoichiometry and response times at all pressure altitudes (see Section 6 on the uncertainty budget). Sites undergoing such change management shall also participate in developing transfer functions required to maintain the homogeneity in the data record.

Ozonesonde expertise outside of GRUAN shall also be used to support the Lead Centre in guiding individual sites through changes in instrumentation without impacting long-term measurement time series.

2.4. Measuring pump flow rate

A common procedure in the ECC conditioning is to use the soap bubble flowmeter method to measure the volumetric flow rate of the pump [sec/100ml]. The required equipment and set-up are described in the ENSCI and SPC manuals [DMT manual, Appendix D, 2014; SPC manual Section 3.2.1, 1999]. Several flow rates are measured and the mean is assigned as the measured flowrate, $\Phi_{Measured}$, applied in Equation 1. The uncertainty of the flow rate is small, generally within ±1% [Smit et al., 2014].

The GRUAN procedure for determining pump flow rate is as follows:

1. The flowmeter equipment provided by ENSCI and SPC is standard and reasonably identical. GRUAN will accept either.
2. GRUAN acknowledges that the soap bubble solution recipe varies among manuals and operators and requires only that the same recipe is used throughout the lifetime of the measurement record.
3. The measurement of the flow rate shall be made five times as required by WMO/GAW and implemented in most SOP.
    i. Flow rates that differ by ±2 sec/100ml or more from the median after measuring the flow rate five times should be repeated.
    ii. Mean $\Phi_{Measured}$ should be between 26 and 32 sec/100ml.
        - Lower and upper limits are chosen by consulting pump flow rate ranges found in the SPC manual [1999] and Smit et al., [2014].
        - If the mean $\Phi_{Measured}$ is not within the acceptable range, this must be recorded in an appropriate data QA/QC flag.
4. The corrected pump flow rate at the ground is expressed as:

Eqn 2.4.1 $$\Phi_{Ground} = [1 + C_{PL} - C_{PH}] \bullet \Phi_{Measured}$$

Where C_{PL} is the correction for the temperature difference between the internal pump base temperature and the ambient room temperature, and C_{PH} corrects for the evaporation of the soap bubble solution (see Komhyr et al. [1995], Johnson et al. [2002], and Smit et al., [2014]). GRUAN shall follow ASOPOS equations to determine C_{PL} and C_{PH}.

Section 6.3 addresses the flow rate uncertainty and its contribution to the ozone measurement uncertainty.

2.5. Estimating degradation in pump efficiency

It has been well documented that the efficiency of the ECC pump decreases at high altitudes [Komhyr, 1967; 1969; 1986; et al. 1995; Johnson et al., 2002; Smit et al., 2014]. Johnson et al. [2002], and references therein, cite pump leakage, dead volume in the piston pump, and back-pressure exerted on the pump by the cell solution as main causes of pump efficiency loss at low pressures. Experiments reveal that the pump flow rate, Φ, measured at the ground is constant up to 100 hPa and decreases steadily to the top of the atmosphere. This is true for the pumps used in both SPC and ENSCI ozonesondes.

Calculated ozone partial pressures must therefore include a correction for the effects of pump efficiency loss. From Equation 1 (in Section 2.1), the pump flow conversion efficiency, Ψ (1/pump correction factor), takes into account the efficiency loss in Φ as a function of pressure. Empirical averages obtained from various lab techniques have yielded pump correction factors (PCF; Komhyr [1986]; Komhyr et al. [1995]). The two most widely used PCF are shown in Table 2.5.1. However, both PCF have been calculated based on SPC ECC type and models older than SPC 6A and the sample sizes are small (e.g. K95 N = 13). GRUAN recommends laboratory studies with statistically significant sample sizes of the standard ECC types/models currently in use to verify or update these PCF and their uncertainties.

Pressure [hPa]	Komhyr, 1986 (K86)	K86 uncertainty, $\Delta\Psi$	Komhyr et al., 1995 (K95)	K95 uncertainty, $\Delta\Psi$
Sfc-100	1.000	1.000	1.000	1.000
100	1.007	± 0.005	1.007	± 0.005
50	1.018	± 0.006	1.018	± 0.005
30	1.022	± 0.008	1.029	± 0.008
20	1.032	± 0.009	1.041	± 0.012
10	1.055	± 0.010	1.066	± 0.023
7	1.070	± 0.012	1.087	± 0.024
5	1.092	± 0.014	1.124	± 0.025
3	1.124	± 0.025	1.241	± 0.043

Table 2.5.1 Pump corrections factors (PCF) with 1-sigma uncertainties. PCF values are taken from the GAW Report No. 201, Table 3-3 [Smit et al., 2014].

Following the recommendations of WMO/GAW report 201 [Smit et al., 2014], GRUAN Ozonesonde programmes shall use the K86 PCF for SPC ozonesondes and K95 PCF for ENSCI ozonesondes as listed in Table 2.5.1. PCF between tabulated values must be interpolated on a log pressure scale with 2nd order polynomial interpolation.

2.6. Measuring pump temperature

The temperature of the ozonesonde pump, T_p, is required in the calculation of the ozone partial pressure (see Equation 1., Section 2.1) to account for the temperature of the air flowing through the pump. Over time, the location of the thermistor used to measure the pump temperature has changed, potentially introducing inhomogenieties into the sounding record [Smit et al., 2014]. Smit et al. [2014] has identified five configurations of T_p measurements based on the placement of the thermistor (see Table 2.6.1) and has characterized their uncertainty relative to the current placement of thermistors in modern ECC sondes, which is inside the pump and is referred to as the internal pump temperature (see Case 5 in Table 2.6.1).

Table 2.6.1

Case	Time Period	Location	Name	Sonde Types	Notes
1	1960- end 1980s	Bottom of circuit board	Box Temperature	SPC 2A, 3A, 4A	Analog sondes
2	1990s	Suspended in the styrofoam box in the vicinity of the pump	Box Temperature	SPC 5A	Start of digital sounding systems. Behaves as in Case 3
3	1990s	Taped thermistor at the pump base	External Pump Temperature	SPC 5A	
4	1990s	Epoxied at the pump base	External Pump Temperature	SPC 5A	Behaves like Case 1
5	> 1995	Mounted inside the pump body, close to the piston	Internal Pump Temperature	ENSCI Z & 2Z, SPC 6A	Current generation ECC soundings

Smit et al. [2014] considers the correct or 'true' T_p as the pump temperature measured in the vicinity of the moving piston, T_{piston}. Based on Komhyr and Harris [1971] and JOSIE 2000 lab experiments [Smit et al., 2007], empirical pressure dependent equations have been formulated to adjust pump temperatures from Cases 1 through 4 to an internal pump based temperature (Case 5). Internal pump temperatures are considered to be the best approximation to the 'true' T_p. Further, lab experiments that compare piston temperatures to internal pump, or pump-based, temperatures (the latter using the empirically derived equations) found a 1-3K difference, prompting an additional equation that corrects for this temperature bias [Smit et al., 2014]. The resultant pump temperature corrections required for each case listed in Table 2.6.1 are:

Case 1: Equation 2.6.1

(a) $T_{Pcase1} = 7.43 - 0.393\text{Log}_{10}(P)$ $\quad P \geq 40$ hPa

(b) $T_{Pcase1} = 2.7 - 2.6\text{Log}_{10}(P)$ $\quad 6 < P < 40$ hPa

(b) $T_{Pcase1} = 4.5$ $\quad P \leq 6$ hPa

Case 2, 3: Equation 2.6.2

(a) $T_{Pcase2,3} = 20.6 - 6.7\mathrm{Log}_{10}(P)$ $P > 70$ hPa
(b) $T_{Pcase2,3} = 8.25$ $15 \le P \le 70$ hPa
(c) $T_{Pcase2,3} = 3.25 - 4.25\mathrm{Log}_{10}(P)$ $5 \le P < 15$ hPa

Case 4: Equation 2.6.3

(a) $T_{Pcase4} = 6.4 - 2.14\mathrm{Log}_{10}(P)$ $P > 40$ hPa
(b) $T_{Pcase4} = 3.0$ $3 \le P \le 40$ hPa

Case 5: No adjustment, i.e. $T_{Pcase5}=0.0$

The additional correction to account for differences between T_{piston} and the internal pump, or pump based, temperatures is described as:

Equation 2.6.4 $T_{piston\text{-}internal} = 3.9 - 0.8\mathrm{Log}_{10}(P)$

Note that equations 2.6.1 to 2.6.4 were derived from small statistical samples (Equation 2.6.4 from a sample of only three ECC sondes in the JOSIE chamber experiments; Figure 9 from Smit et al. [2007]). The adjustment formulae for Cases 2 and 3 were derived from a sample size of eight, while only three sondes were used to generate the Case 4 formula. The uncertainties inherent in the small samples underlying equations 2.6.1 to 2.6.4 must be propagated through to the uncertainties in the derived ozone partial pressures. Section 6.5 summarizes the pump temperature uncertainty parameters and equations and how these contribute to the ozone partial pressure uncertainty.

The ASOPOS panel recommends that the final adjusted pump temperature, T_p, be used to calculate the ozone partial pressure, should be defined as:

Equation 2.6.5 $T_p = T_{measured} + T_{Pcase\_i} + T_{piston\text{-}internal}$

where $T_{measured}$ is the pump temperature recorded by the sonde, T_{Pcase_i} is the correction that depends on the case, and $T_{piston\text{-}internal}$ is the additional correction defined by equation 2.6.4.

2.7. Determining the partial ozone column above the top of flight

GRUAN's purpose for calculating total column ozone for each profile is to allow for comparisons against an independent spatially and temporally co-located total column ozone measurement to provide a means of validating the quality of the ozonesonde ozone profile. The standard technique for computing total column ozone from an ozonesonde measurement includes adding a climatological ozone partial column value above the balloon burst altitude. Most often, these partial columns are based on satellite and ozonesonde observations [McPeters et al, 1997, 2007, 2012; Labow et al., 2015], although some sites have developed their own monthly climatologies, e.g. based on microwave radiometer-derived ozone profiles. Comparisons of the integrated ozonesonde ozone profile plus the partial column above the top of flight can then be made with ground-based and satellite measurements of total column ozone (e.g. Dobson spectrophotometer, Brewer spectrometer, OMI, GOME-2).

GRUAN encourages sites to include any ancillary measurements of surface and column ozone measurements in the metadata submitted to the centralized GRUAN ozonesonde data processing facility. Redundancy in ozone measurement systems provides a powerful tool for validating and evaluating the ozone measurements in any given time series.

The GRUAN ozonesonde data product shall adopt the following guidelines:

- The integrated ozone column amount (in DU) up to 10 hPa or balloon burst, whichever is lower. Profiles above 10 hPa have high uncertainty due to the degradation of the pump efficiency [Witte et al., 2017].
- Total column ozone from ozonesondes shall only be calculated where the balloon bursts above the ozone peak.
- The ozone residual column amount (in DU) above burst pressure and ozone peak can use the McPeters et al. [2012] climatology, an updated version, or a site-specific climatology shall that has been peer-reviewed and shown to be as accurate, of not more so, than commonly used ozone residual climatologies.
- It is recognized that there may be gaps in the profile measurements due to intermittent telemetry. Profiles with large data gaps shall be identified and evaluated on a case-by-case basis and the flight total column ozone value and, importantly, its uncertainty, calculated according.
- If available, co-located ground-based or space-based measurements of total column ozone shall be included.

2.8. Dependence on the radiosonde

Radiosonde pressure and temperature measurements are used to calculate the geopotential heights. Thus, radiosonde measurement errors will cause the measured ozone to be assigned incorrect altitudes and pressures. As with ozonesondes, there are a number of radiosonde manufacturers whose instruments have changed in model, material, and algorithm since the 1970s. There are measurable differences between manufacturers, i.e. Vaisala vs iMET (Stauffer et al., 2014), and between models, i.e. Vaisala RS-80 vs RS-92, that impact the ozonesonde measurement, particularly at low pressures [Smit et al., 2014; and references therein]. GRUAN shall document radiosonde manufacturer, model and type of interface so that appropriate calibrations and corrections to the pressure and temperature, as well as RH, can be made in the pre- and post-processing calculations of the geopotential height.

GRUAN procedure protocol

- Calibration of the radiosonde surface pressure, temperature, RH and determination of any offset between geopotential and GPS height measurements, if and when available, shall follow the processing guidelines dictated by the GRUAN Radiosonde Technical Document.
- Handling biases in the geopotential height calculation in the absence of GPS measurements shall be the responsibility of the Task Team Radiosondes, WG-GRUAN, and Lead Centre.

- Radiosonde/Ozonesonde offsets in height and pressure, if any, shall be documented and geopotential heights shall be recalculated by the Lead Centre GOASS (refer to Section 3.7).
- Quantifying the contribution of the radiosonde uncertainty to the ozone measurements, if any, shall be the responsibility of the Task Team Radiosondes, WG-GRUAN, and Lead Centre.

2.9. Conversion efficiency

One of the terms in the ozone uncertainty calculation is the contribution of the uncertainty in the conversion efficiency. The conversion efficiency refers to 1:1 ratio assumed in the I_2:O_3 relationship. Interferences with this one-to-one relationship can arise from the buffering of the solution [Johnson et al. 2002; Vömel and Diaz, 2010]. The cathode solution contains a buffer of sodium-hydrogen phosphate to maintain the solution concentration and a neutral pH of 7.0 during flight. GRUAN shall follow a half buffered cathode solution for ENSCI sensors and a full buffer for SPC, as recommended by WMO/ASOPOS [Smit et al., 2012; 2014]. Johnson et al. [2002] performed stoichiometric sensitivity and pH tests and measured excess ozone at low pressures due to the buffering effect. This would yield an I_2:O_3 relationship larger than unity. This offset in the stoichiometry has been documented by others (Smit et al., 2014, section 3.2.2 and references therein; Johnson et al, 2002, section 2.1 and references therein). In the ozone partial pressure equation, Equation 1, the conversion efficiency is assumed to be unity and is therefore excluded from the equation. However, the uncertainty of this unity assumption can be a significant contributor to the ozone uncertainty estimates and is addressed in Section 6.6.

2.10. Transfer Functions

There have been a number of studies that have used laboratory, dual-sonde, and multi-sonde payloads to derive methods of calculating transfer functions that characterize differences in instrument and solution concentration [Smit et al., 2007; Kivi et al., 2007; Deshler et al., 2008; Stübi et al., 2008; Mercer et al., 2008; Deshler et al., 2017].

As part of the SPARC-IGACO-IOC-NDACC (SI2N) initiative, the Assessment of Standard Operating Procedures for Ozone Sondes (ASOPOS) working group established empirical transfer functions specifically for the SPC and ENSCI type ozonesondes using either the 1% full buffer or 0.5% half buffer solutions [Smit et al., 2012]. These formulae are based on work done by Deshler et al., [2017] which uses all data taken from the above campaigns. Their aim is to homogenize long-term ozonesonde records that use these sensor/solution combinations for ozone assessments of changes in the vertical distribution of ozone [http://igaco-o3.fmi.fi/VDO/documents.html].

These transfer functions represent the quantitative differences of the ozonesonde response based on changes in instrumentation and stoichiometry of the conversion of O_3 to I_2 with a change in solution concentration. They are not a reflection of changes in SOP. Smit et al. [2007] and Thompson et al. [2007] showed that there are discontinuities in the time series of a single site that have used a variety of instruments and solution strength, citing the need to homogenize the long term records of individual ozonesonde sites. The conversion relationship is summarized in Table 3 of Smit et al. [2012].

GRUAN processing protocol

1. Where applicable, transfer functions derived by Deshler et al. [2017] shall be applied and be part of the ozonesonde Standard GRUAN Data Product (SGDP).
2. Data records where transfer functions should be applied but do not yet exist shall remain in the Level 2 stage and shall not be considered as part of the ozonesonde SGDP.
3. Transfer functions for time series that use a combination of BM and ECC shall follow WMO/GAW #201 Report guidelines found in Section 4.3 and subsections. It shall be the responsibility of the Lead Centre and the WG-GRUAN to evaluate the appropriateness of the transfer functions and determine if BM data records are of sufficient quality to meet the GRUAN reference measurement standards.
4. As of this document, there are no transfer functions for time series that use a combination of CI and ECC sondes. However, dual sonde launches have been conducted by Nakamura et al., [2008] and have the potential to be used to develop transfer functions. The Lead Centre and WG-GRUAN shall work with the manufacturer (Japanese Meteorological Agency) to determine the extent to which uncertainties estimates have been established and validated and the status of deriving transfer functions between CI and ECC sondes by the group. It shall be the responsibility of the Lead Centre and the WG-GRUAN to evaluate the appropriateness of the transfer functions and determine if the historic CI data records are of sufficient quality to meet the GRUAN reference measurement standards.

3. THE OZONE UNCERTAINTY BUDGET

The measurement uncertainty of the ozonesonde system describes the current best knowledge of instrument performance under the conditions encountered during an observation. This section summarizes how the centralized GRUAN Ozonesonde Analysis Software System (GOASS) processes the uncorrected and original ECC ozonesonde data to produce an ozonesonde SGDP.

The assessment of the uncertainty budget of ozone measured from ozonesondes is a complex task. Measurement uncertainties in ozonesondes should, in the first instance, be characterized in the laboratory. JOSIE (Jülich Ozonesonde Inter-comparison Experiment) has played a key role in describing/analyzing all sources of ECC measurement uncertainty to the extent possible, quantifying/synthesizing the contribution of each source of uncertainty to the total measurement uncertainty, and verifying that the derived net uncertainty is a faithful representation of the true uncertainty and is in agreement with the required (expected) target uncertainty.

With regards to the BM and CI type sondes, it shall be the responsibility of the Lead Centre and the WG-GRUAN to evaluate the appropriateness of uncertainty estimates and determine if BM and CI data records are of sufficient quality to meet the GRUAN reference measurement standards (see Section 8 on Quality Management).

3.1. The ozone uncertainty equation

Since the 1990's tests conducted by JOSIE-led experiments, campaigns such as BESOS, and dual flight experiments have clearly demonstrated the need to characterize singular features of the ECC ozone sensors and standardize measurements. These activities have lead to the creation of the ASOPOS panel whose goals are to (i) standardizing the ozonesonde conditioning and preparation procedures, (ii) establishing guidelines for the reprocessing and homogenization of ozonesonde data records, and (iii) determining the contributions of the individual uncertainties of the different instrumental parameters to the ozone measurement. The treatment of uncertainty in the GRUAN ozonesonde data processing will follow the recommendations and definitions of the ASOPOS panel documented in Smit et al. [2012]. These uncertainty parameters are part of the ozonesonde SGDP. We provide only a brief summary of uncertainty calculations derived for each variable in the ozone partial pressure equation (Eqn. 1). GRUAN shall adopt the following ozone uncertainty equation taken from Equation E-3-2 in Smit et al., [2012]:

Eqn. 3.1.1

$$\frac{\Delta P_{O3}}{P_{O3}} = \sqrt{\frac{(\Delta I_M)^2 + (\Delta I_B)^2}{(I_M + I_B)^2} + \left(\frac{\Delta \eta_C}{\eta_C}\right)^2 + \left(\frac{\Delta \Phi_{Ground}}{\Phi_{Ground}}\right)^2 + \left(\frac{\Delta \mathrm{T}_P}{\mathrm{T}_P}\right)^2 + \left(\frac{\Delta \Psi}{\Psi}\right)^2}$$

where the term, $\left[(\Delta I_M)^2 + (\Delta I_B)^2\right] / (I_M + I_B)^2$ is the contribution of the uncertainty in background current, the $(\Delta \eta_C / \eta_C)^2$ term is the contribution of the conversion efficiency uncertainty, the $(\Delta \Phi_{Ground} / \Phi_{Ground})^2$ term is the pump flow rate uncertainty at the ground, the $(\Delta \mathrm{T}_P / T_P)^2$ term is the contribution of the pump temperature, and the $(\Delta \Psi / \Psi)^2$ term is the pump flow correction factor uncertainties. Equation 3.1.1 is the sum of the squares of the uncertainty in each term of the ozone partial pressure equation (Section 2.1, Eqn. 1). The uncertainties are assumed to be random and gaussian and therefore follow the gaussian law of error propagation. Each instrumental uncertainty term is discussed briefly in subsequent sections.

3.2. Contribution of the uncertainty in background current

The term $\left[(\Delta I_M)^2 + (\Delta I_B)^2\right] / (I_M + I_B)^2$ from equation 3.1.1 is the contribution of the uncertainty in background current, where ΔI_M is the uncertainty in the measured current, I_M, and ΔI_B is the uncertainty in the background current, I_B.

There is no standard or statistically robust method for estimating the uncertainty of the background current. JOSIE experiments used small sample sizes, less than 14 ECC sensors, to conduct the background current experiments published in Smit et al, [2007] and ultimately used in the WMO/ASOPOS guidelines [Smit et al, 2012; 2014]. Results from Table 7 of Smit et al. [2007] record an average I_{B0} measurement ('background current before O_3-exposure') and 1-sigma uncertainty of 0.02±0.02 μA using ENSCI sensors with a 0.5% half buffer KI solution and 0.023±0.013 μA using Science Pump Corporation (SPC) sensors with a 1.0% full buffer KI solution.

Based on the JOSIE results above, for ozonesonde sites that use I_{B0} as their final background, GRUAN will adopt a ±0.02 µA background current uncertainty, ΔI_B, for ENSCI 0.5% half buffer KI solution and a ±0.013 µA uncertainty for Science Pump ECC 1.0% full buffer KI solution because there are no other uncertainty estimates for I_{B0} in the literature. Furthermore, there is the added complication that this is a single measurement per unique ECC sensor so uncertainties cannot be directly ascertained.

For sites that use I_{B2} as the final background current, GRUAN will adopt a ±0.03 µA uncertainty for ENSCI/0.5% and ±0.02 µA for SPC/1.0% based on results from Witte et al., [2017].

The uncertainty in the ozone current, ΔI_M, shall be set to 0.1 µA which is the resolution of the digital interface board (Terry Deshler/UWy and Herman Smit/Forchungszentrum, personal communication).

The uncertainty constants for the standard pairs are summarize in Table 3.1.1 below.

Table 3.1.1 Constants in the ozone current uncertainties for standard ECC/Solution pairs.

ECC/Solution	**Final I_B**	**ΔI_B**	**ΔI_M**
ENSCI/0.5%	I_{B0}	±0.02 µA	±1% of measured currents above 1 µA, and ±0.01 µA for currents below 1 µA.
	I_{B2}	±0.03 µA	
SPC/1.0%	I_{B0}	±0.013 µA	
	I_{B2}	±0.02 µA	

Background uncertainties outside the ENSCI/0.5% and SCP/1.0% pairs shall have to undergo similar rigorous testing to establish uncertainty estimates. In this case, profiles shall be archived until such time as background uncertainties can be establish and applied to create the ozonesonde SGDP. SGDP cannot be generated unless all uncertainty contributions to ozone in Equation 3.1 are known.

3.3. Contribution of the uncertainty in pump flow rate at the ground

From Section 2.4 Equation 2.4.1 the final mean flow rate is corrected for the humidification effect, C_{PH}, and differences between the internal pump temperature and the ambient air, C_{PL}.

The full equation to calculate the pump flow rate uncertainty at the ground is expressed in the following equation

Equation 3.3.1

$$\frac{\Delta\Phi_{Ground}}{\Phi_{Ground}} = \sqrt{\left(\frac{\Delta\Phi_{Measured}}{\Phi_{Measured}}\right)^2 + \left(\Delta C_{PL}\right)^2 + \left(\Delta C_{PH}\right)^2}$$

The uncertainty in C_{PH} and C_{PL} are site specific. For existing sites that have established at least one year's worth of ozonesonde launches, i.e. a minimum of 24 total launches, relative uncertainties, ΔC_{PH} and ΔC_{PL}, can be calculated following Smit et al., [2012] recommendations (See section 8.4).

For new GRUAN Ozonesonde Programmes with no launch history it is impossible to estimate ΔC_{PH} and ΔC_{PL}. In this case, the term shall not be used in the ozone uncertainty equation until after one years worth of ozonesonde launches have been processed by the GRUAN Lead Centre. Until such time, profiles shall be archived until ΔC_{PH} and ΔC_{PL} can be calculated and then used to create the ozonesonde SGDP. These terms will change as the data record expands, thus ΔC_{PH} and ΔC_{PL} should be continually re-evaluated by the Ozonesonde Programmes annually to check for large deviations from its constant value and assess whether and how fluctuations in the uncertainty terms affect the ozone uncertainty significantly. It may be that re-processing of the entire data record of a given site is required if ΔC_{PH} and ΔC_{PL} statistics changes significantly over time.

3.4. Contribution of the uncertainty in pump correction factor (PCF)

The uncertainty in the pump correction factors (PCF), $\Delta\Psi$, shall be taken from Table 2.5.1. Calculating $\Delta\Psi$ between data points shall be done on a log pressure scale with 2nd order polynomial interpolation. The GRUAN GOASS shall use the following PCF uncertainties to the following ECC sensors:

(i) K86 $\Delta\Psi$ for SPC ECCs
(ii) K95 $\Delta\Psi$ for ENSCI ECCs.

New ECC sensors shall have to undergo similar JOSIE testing, laboratory and field tests to establish and validate their PCF values and uncertainties. GRUAN protocols for managing a change in sensor technology shall follow guidelines put forth in Section 7.1.

3.5. Contribution of the uncertainty in pump temperature

Calculating the adjusted pump temperature is discussed in detail in Section 2.6 and the associated uncertainties are summarized in Table 3.5.1 below. Note that all units are in degrees Kelvin.

Table 3.5.1 Uncertainties based on the location of the pump temperature thermistor.

Case	Location	Sonde Type	ΔT_P	ΔT_{PCase}	$\Delta T_{Piston\text{-}internal}$
1	Bottom of circuit board	SPC 2A, 3A, 4A	±1.0K	±1.0K	±0.5K
2	Suspended in the styrofoam box in the vicinity of the pump	SPC 5A	±0.5K	$3.9–1.13\mathrm{Log}_{10}(P)$ for $P > 70$hPa $3.0–1.13\mathrm{Log}_{10}(P)$ for $P \leq 70$ hPa	±0.5K
3	Taped thermistor at the pump base	SPC 5A	±0.5K	Same as Case 2	±0.5K
4	Epoxied at the pump base	SPC 5A	±0.5K	±0.5K	±0.5K
5	Mounted inside the pump body, close to the piston	EnSci Z & 2Z, SPC 6A	±0.5K	No uncertainty	±0.5K

The additional correction to account for differences between moving piston, T_{piston}, and the internal pump, or pump based, temperatures is defined as $\Delta T_{piston\text{-}internal} = \pm 0.5K$ and is true for all cases.

The full contribution of the measured pump temperature to the ozone uncertainty is expressed as

Equation 3.5.1
$$\frac{\Delta T_P}{T_P} = \sqrt{\left(\frac{\Delta T_P}{T_P}\right)^2 + \left(\frac{\Delta T_{case\_i}}{T_P}\right)^2 + \left(\frac{\Delta T_{piston-internal}}{T_P}\right)^2}$$

3.6. Contribution of the uncertainty in the conversion efficiency

GRUAN shall adopt the WMO/GAW uncertainty calculation for the conversion efficiency [Smit et al., 2014, Equation E-3-4], written as

Equation 3.6.1
$$\frac{\Delta \eta_C}{\eta_C} = \sqrt{\left(\frac{\Delta \alpha_{O3}}{\alpha_{O3}}\right)^2 + \left(\frac{\Delta S_{O3:I2}}{S_{O3:I2}}\right)^2}$$
where,

$\Delta\eta_C/\eta_C$ = conversion efficiency uncertainty term
α_{O3} = absorption efficiency from the gas into liquid phase of the sensing solution = 1.0
$\Delta\alpha_{O3} = \pm 0.01$
$S_{O3:I2}$ = stoichiometry of the conversion of O_3 to I_2 = 1.0
$\Delta S_{O3:I2} = \pm 0.02$ at Z=0km with a linear increase to ± 0.05 at Z=35km. This translates to the linear equation, $\Delta S_{O3:I2}(Z) = 0.000857143 * Z + 0.02$

Setting the absorption efficiency (α_{O3}) equal to one applies to cases where the volume of the cathode solution is 3.0 cm^3. GRUAN will use the following WMO/GAW equations to calculate α_{O3} for a 2.5 cm^3 volume, as follows

Equation 3.6.2 $\quad \alpha_{O3}(P) = 1.0044 - 4.4x10^{-5} * P \quad 100 \text{ hPa} < P < 1050 \text{ hPa}$
Equation 3.6.3 $\quad \alpha_{O3}(P) = 1.0 \quad P \leq 100 \text{ hPa}$

$\Delta\alpha_{O3}$ is ± 0.01 for both cathode volumes.

GRUAN shall require new candidate sites to use 3.0 cm^3 volume cathode sensing solution to reduce added uncertainty in the ozone uncertainty equation and maintain a constant absorption efficiency throughout the profile measurements.

3.7. Contribution of the uncertainty in the radiosonde pressure to ozone uncertainty

The designated GRUAN Ozonesonde Lead Centre shall adopt the GRUAN Radiosonde Technical Report processing procedures for calculating the uncertainties associated with the radiosonde measurements. Handling biases in the geopotential height calculation in the absence of GPS measurements shall be the responsibility of the Radiosonde WG-GRUAN, assigned task team, and responsible Lead Centre.

4. GRUAN OZONESONDE PROGRAMMES

The GRUAN Guide (GCOS-171) states that the primary objective of GRUAN is to provide reference measurements for a range of upper-air climate variables. Reference quality observations are based on key concepts in metrology, in particular traceability. Metrological traceability is the process whereby a measurement and its uncertainty, can be related to a reference through a documented, unbroken chain of calibrations.

Confidence in the long-term stability of the ozonesonde data records across the network as a whole, the instrumentation, SOP, and data processing must be established in such a way that measurements from individual GRUAN Ozonesonde Programmes generate data sets that are homogeneous in both space (i.e. across the network) and time. For this reason, certification of GRUAN Ozonesonde Programmes (see Section 4.1) applies to the overall infrastructure underlying the ozonesonde measurement and the subsequent production of a final GRUAN ozonesonde reference data product. This infrastructure is defined here as a GRUAN Ozonesonde Programme, and includes the:

1. SOP that prescribe how ozonesonde flights shall be performed at a GRUAN site,
2. Mandatory collection of metadata used to characterize the singular features of each ozonesonde and its inflight performance,
3. Acquisition of the uncorrected original data and metadata by the RSLaunchClient utility (GRUAN-TD-3) for central processing,
4. Steps involved for creating a final homogenized GRUAN ozonesonde data product,
5. Storage and dissemination of the GRUAN ozonesonde data product.

To be GRUAN-certified each GRUAN Ozonesonde Programme must provide to the Lead Centre and to the GRUAN centralized ozonesonde data processing facility a GRUAN Ozonesonde Instrumentation and Measurement Report (GOIMR). This document describes the site's ozonesonde measurement programme and capabilities, as well as documenting the history of its ozonesonde data record, if any. The GOIMR shall include all aspects of the programme such as instrumentation inventory, SOP used, measurement schedules, and up-to-date data acquisition and archiving status. In addition, the site must provide proof of its ability to provide all essential metadata (defined in Section 4.6) and original data to the central processing facility using the RSLaunchClient utility (GRUAN-TD-3). All ozonesonde metadata uploaded by the RSLaunchClient shall be consistent with the latest version of a recommended check list (examples found in Appendix A-1 and in Appendix A-2 for refurbished sondes). Once certified, GRUAN Ozonesonde Programmes will be audited at least quadrennially, and reviewed annually to confirm compliance with the requirements and recommendations of GCOS-171 and this Technical Document.

4.1. GRUAN Ozonesonde Programme site assessment and certification

Sites seeking to have their ozonesonde measurements certified as a GRUAN Ozonesonde Programme will be assessed using criteria described in this section. In addition, each such site seeking certification must follow the requirements regarding site assessment and certification described in Section 5.1 of GCOS-171.

GRUAN recognizes that sites will vary in infrastructure and financial support. To comply with the mandatory operating protocols defined in Section 5.3 of GCOS-171, each GRUAN Ozonesonde Programme must:

1. Provide reference quality ozonesonde measurements, i.e., observations characterized by traceable calibrations, readily accessible documentation, and complete metadata availability.
2. Assure long-term storage of these data either at the site, at another GRUAN facility, or at another internationally accessible archive in accordance with the GRUAN Data Policy document (referred to in Section 8.2 GCOS-171).
3. Provide, to the extent possible, redundant reference observations of the vertical ozone profile or total column measurements from co-located ground-based instruments for independent evaluation and validation of the ozonesonde measurements and their uncertainties.
4. Provide annual reports summarizing the ozonesonde operations at the site, including any changes in instrumentation, how those changes were managed, and any improvements made in the Programme.
5. Manage change proactively as defined in Section 7 of this Document.
6. Actively communicate with the GRUAN Lead Centre, WG-GRUAN and GRUAN TTR through attendance at meetings and emails.

Specifically, certification of a GRUAN ozonesonde programme shall be cognizant of:

1. The content and completeness of the GOIMR each ozonesonde candidate site is required to file.
2. The level to which the candidate ozonesonde site conforms to the GRUAN prescribed SOP which is necessary to guarantee data product homogeneity across the network. Determining whether the operating procedures of an existing site meet the prescribed SOP will be done against the requirements outlined in Section 4.5. Metadata requirements are addressed in Section 4.4.3.
3. Added value the candidate site brings to the GRUAN network of ozonesonde programmes, as a whole. This is outlined in detail in Section 4.2.1.

4.2. GRUAN Ozonesonde Programme assessment and certification process

Two scenarios are foreseen:

1. The candidate site has no other GRUAN certified measurement programme.
2. The candidate site has at least one other GRUAN certified measurement programme.

In the case of scenario (1) the certification of the site's ozonesonde programme also constitutes certification of the site as a GRUAN site. Refer to GCOS-171 for the additional requirements for site certification under scenario (1). Under either scenario, the following sequence of events defines the process specific to the certification of the GRUAN Ozonesonde Programme at the site:

1. The GRUAN Lead Centre will provide the site with this Document, as well as any additional documentation related to data submission protocols and the procedures that must be followed when data are submitted to the GRUAN ozonesonde central data processing facility.

2. The response from the candidate site shall be given in the form of the GOIMR submitted to the GRUAN Lead Centre and should include:

    2.1. A complete description of how the ozonesonde measurement programme will be conducted. Such information would include launch frequency and scheduling, detailed SOP, a copy of the check list and metadata inventory, and data storage policies. This information must be sufficient to establish the capability of the site to meet the mandatory operating protocols outlined in Sections 4.5 - 4.7.
    2.2. Include any cooperative agreements with other sites. This is desirable to ensure that expertise is disseminated to similar measurement programmes in operation at other sites.
    2.3. The management structure of the site and a general description of the manner in which the site is operated. This should include a description of current and expected future funding levels for ongoing operation of the site.
    2.4. A description of which data centres the ozonesonde measurements are, in addition to GRUAN, being submitted to and have been submitted to in the past.
    2.5. A description of how past ozonesonde measurements have been processed. This will be used to assess whether the time series to date meets the standards for a GRUAN reference measurement. Particularly important in this regard will be detailed documentation about how changes in SOP over the history of the measurement programmes have been managed to derive a homogeneous time series of measurements.
    2.6. A description of past metadata data records and storage. This will be used to assess whether the time series to date meet the traceability standards for a GRUAN reference measurement.
    2.7. A list of the ozonesonde experts, if any, employed at the site who would likely participate in the analyses of the data collected at the candidate site and who could share their expertise with other GRUAN sites. This may include mention of experts at partnering scientific organizations.

3. There is likely to be some iteration between the Lead Centre and the candidate site to confirm specific details, fill in information gaps, and finalize the documentation from the candidate site.
4. Based on the documentation received from the candidate site, the Lead Centre will then write a short recommendation. This, together with the documentation from the candidate site, will be submitted to the WG-GRUAN who will evaluate the proposal within 3 calendar months against the requirements listed in Sections 4.5 and 4.6. One or more visits to the site by members of the WG and/or Lead Centre within this 3-month period may be required to obtain specific additional information about the ozonesonde measurement programme. If accepted, the ozonesonde programme will then be included in the GRUAN certification for the site.

5. Regardless of the outcome, the WG-GRUAN and Lead Centre will provide written constructive feedback to the candidate site outlining the strengths and weaknesses of their programme for GRUAN purposes and suggestions as to future improvements for GRUAN operational purposes. This feedback is non-binding and is rather intended to provide useful guidance and support.

6. Annual reports shall summarize the operation of the Ozonesonde Programme at the site, identifying any changes in the instrumentation used in the programme (e.g. ozonesonde type, radiosonde type, ground-check equipment), scheduling, procedures, and any improvements implemented. The intent of the annual report is to ensure that GRUAN ozonesonde SOP have been adhered to, and to identify changes that may require additional reprocessing that have not already been taken into account or require re-assessment of GRUAN certification. These reports will be presented at annual GRUAN meetings.

4.2.1 Criteria for assessing added value

The GRUAN Ozonesonde Programme assessment and certification process follows closely the more general GRUAN site certification process described in Section 5.5 of GCOS-171. Achieving all of the measurement programme requirements is not mandatory for the inclusion of a site in GRUAN. The extent to which a site can meet Section 4.1 requirements will determine, in part, the additional value that that site brings to the network. Once a site has committed to supporting the minimal set of measurement programmes under the protocols defined in Section 5.2.2 of GCOS-171, the added value that a site flying ozonesondes brings to GRUAN will be assessed according to:

- *Location*. For example, programmes located in a large region of the globe containing no other GRUAN Ozonesonde Programmes and fulfilling all other minimum requirements of a site will be assessed as adding more value to the network than a site located close to other GRUAN sites making ozonesonde measurements.
- The extent to which the site provides profile measurements of ozone in regions of atmospheric phenomena which were not previously sampled by the network.
- The extent to which the site contributes unique observational and/or analysis capabilities aligned with GRUAN’s scientific objectives and the likelihood of being able to propagate those capabilities across other sites in the network.
- The extent to which the site is prepared to forgo locally established ozonesonde operating procedures and adhere to the SOP detailed in this Document (see Appendix A.1).
- The availability of historical measurements that conform to the GRUAN standard. All else being equal, a candidate site that extends an existing multi-decade time series of reference quality ozonesonde measurements will be assessed as adding more value to the network than a site that would initiate the same measurement programme starting at the present. Detailed documentation in the GOIMR would be required describing how changes in SOP, instruments, calibration procedures, data processing algorithms and operators over the history of the measurement programmes have been managed to ensure that the historical measurements are reference quality. Where historical reference quality measurements are available, consideration will be given by the Lead Centre to provide these as GRUAN data through the GRUAN data archives.

- The extent to which the site can provide redundant observations of the vertical ozone profile or can conduct periodic inter-comparisons and laboratory studies.
- The extent to which a site is capable of measuring other ECVs identified in GCOS-112 as being desired quantities.
- The level of institutional support for the site and commitment to maintaining long-term reference quality measurement programmes. If, in addition, a site can demonstrate that it is actively pursuing resources to enhance its capability, such as the addition of new measurement programmes. It is also desirable that there is full host institution commitment to GRUAN-related activities and that this commitment is not dependent on a single individual.
- The level of institutional support for the site (and any partner institutions) to undertake fundamental scientific research of the measurements from the site and other GRUAN sites. Because GRUAN includes aspects of both operational and research networks, a strong and ongoing science programme is required to ensure that GRUAN fulfills its role as a research network.
- The degree of historical or planned cooperation with other sites both within and outside GRUAN including other GRUAN-relevant networks e.g. NDACC, SHADOZ, GAW, and WOUDC.

Such assessments of added value shall rely on the expert judgement of the WG-GRUAN and Lead Centre.

Determining optimal locations for GRUAN sites intending to fly ozonesondes shall consider:

1. The representation of major climate regions.
2. The ability of the ozonesonde network to diagnose dynamically driven changes in ozone e.g. stratosphere-troposphere exchange, the QBO, regional tropospheric ozone pollution, and regions where halogen-induced ozone depletion is expected.
3. The ability of the network to provide measurements across a range of environments, e.g. tropics, mountainous, deserts, and islands.

4.3 GRUAN Ozonesonde Training Programme

A component of uncertainty in the GRUAN ozonesonde data product may be related to instrument set-up and operation. To minimize these sources of uncertainty, and to ensure network-wide homogeneity of ozonesonde instrument operation, the Lead Centre and WG-GRUAN shall identify Ozonesonde Programmes where instrument operators would benefit from training on GRUAN ozonesonde SOP, and shall organize cost-efficient training courses. A designated Ozonesonde Programme representative at each participating GRUAN site who is primarily responsible for the operation of that programme, should attend an initial training session in which the GRUAN-specific ozonesonde best measurement practices, and the use of RSLaunchClient are taught. Training of new or additional members of the ozonesonde team at a GRUAN site can either be done by the GRUAN Ozonesonde Programme site representative, and ozonesonde expert, or at a training session at a GRUAN site where SOP are kept up-to-date.

For those GRUAN Ozonesonde Programmes already partnered with an ozonesonde expert, training and maintaining up-to-date practices shall be coordinated between the two partners.

Sites hosting GRUAN Ozonesonde Programmes where re-training is sought can make a formal written request for re-training to the Lead Centre. It is also possible that the WG-GRUAN may, on reviewing a site's annual report, request re-training to guarantee consistency of quality. Finally, an audit (see Section 4.10) may reveal deficiencies in the operating procedures that would trigger the need for re-training.

4.4. GRUAN Ozonesonde Programme data management

General considerations shall follow those detailed in Section 8 of GCOS-171.

4.4.1 Overview of the data flow

Refer to Figure 3 of GCOS-171 that shows a schematic representation of the flow of data in GRUAN to the user community.

GRUAN data levels relevant to ozonesondes are based on the GRUAN Data Management Manual:

- Level 1 (L1): Converted raw data (CRD). This is telemetry data convert by the ozonesonde ground station to a common well-described file format intended for long-term storage. They are pre-processed ozone data that have not yet had the necessary corrections and transfer functions applied and might already represent parameters to be used in an end-user's application.
- Level 2 (L2): SGDP resulting from all processing steps applied to the Level 1 data from a single flight.

Measurements and metadata are bound together in each of these data levels. CRD are ingested from all GRUAN sites hosting an Ozonesonde Programme into the internal GRUAN data archive for ozonesonde data.

From CRD data submission to processing, storing and dissemination of SGDP

1. Level 1 CRD and metadata shall be collected by the RSLaunchClient utility. Only original data that have not been processed apart from the ground station data acquisition system shall be submitted to the RSLaunchClient utility.
2. Each GRUAN site is responsible for back-up storage of the CRD and associated metadata in its original format and in digital format.
3. Processing of the ozonesonde CRD will be held in the designated GRUAN internal data archive at the Lead Centre.
4. The Lead Centre GOASS will be responsible for taking the CRD and metadata to create the final standard ozone products (SGDP), as outlined in Section 4.7. This processing should include applying the necessary corrections, transfer functions, and uncertainty estimates in a consistent and traceable manner across identical instrument/solution pairings from other Ozonesonde Programmes.
5. The SGDP, including their metadata, will be provided to the user community through the external GRUAN data archive hosted at NCEI.

A performance monitoring process (see Section 9 of GCOS-171), implemented at the Lead Centre, will provide feedback on performance to individual sites.

4.4.2 GRUAN data policy

Since GRUAN is co-sponsored by WMO, GRUAN ozonesonde data dissemination and use shall comply with WMO Resolution 40 (Cg-XII) which calls for free and unrestricted international exchange of data. Refer to Section 8.2 of GCOS-171 for further details on the data dissemination and exchange policy.

4.4.3 Collation of Metadata

To provide the best evaluation for the ozonesonde measurement uncertainty, a detailed understanding of the instrumentation is required for the conditions under which it is used. The ozonesonde metadata summarizes the unique characteristics of each ozonesonde instrument in response to standard operational procedures, and it makes all factors that contribute to the measurements traceable. Metadata shall be collected from a specified check list sheet that GRUAN ozonesonde site operators shall use. An example is the SHADOZ check list sheet found in Appendix A.1 that goes beyond the minimum metadata requirements recommended by WMO/GAW. The RSLaunchClient utility will be responsible for ingesting profile metadata to be saved and stored at a designated GRUAN archive. A candidate site should demonstrate that all essential metadata found in A.1 are recorded and shall be submitted to the RSLaunchClient utility. Ozonesonde Programmes are required to keep original copies of their metadata at their own storage facility, as secondary storage back-up.

Metadata documents related to historical operations at GRUAN sites and to historical data archives should be inventoried and properly conserved until such time as their information content can be transferred to a medium which supports multiple users' access and conforms to GRUAN reference measurement guidelines.

Metadata needs to have the same level of commitment as observed data. Incomplete, outdated, or inaccurate metadata can be as detrimental, indeed in some cases worse, than no metadata at all. Regular reviews of metadata content for confirmation and accuracy should be part of regular GRUAN operations.

4.4.4 Ozonesonde Standard GRUAN Data Product

The GOASS shall use the CRD, in conjunction with the metadata also collected from the RSLaunchClient, to generate the ozonesonde SGDP. Section 4.7 goes through the GOASS steps required to generate the ozonesonde SGDP from the CRD. The family of ozonesonde SGDP are listed in Table 4.1. Apart from the uncertainty estimates, it is not mandatory for all variables under the ozonesonde SGDP family to be measured. For example, heritage ozonesonde measurements used radiosondes that did not have the means or capability of acquiring GPS information.

Table 4.1 Collection of Ozonesonde SGDP

1. Time [s]
2. Radiosonde Pressure [hPa]
3. Radiosonde Pressure Offset [hPa]
4. Geopotential height [gpm]

5. Radiosonde Temperature [K]
6. Radiosonde Temperature Offset [K]
7. Radiosonde Relative Humidity [%]
8. Radiosonde RH offset [%]
9. Radiosonde Horizontal Wind Direction [decimal degrees] (range: 0:360)
10. Radiosonde Horizontal Wind Speed [m/s]
11. Radiosonde GPS Geometric Height [m]
12. Radiosonde GPS Longitude [decimal degrees] (range: -180:+180)
13. Radiosonde GPS Latitude [decimal degrees]
14. Rise rate [m/s]
15. Ozone Partial Pressure an uncertainty [mPa]
16. Ozone Mixing Ratio per volume [ppm]
17. Box or Pump Temperature and uncertainty [K]
18. Ozone Current and uncertainty [µA]
19. Background Current and uncertainty [µA]
20. Pump Flow rate and uncertainty
21. PCF and uncertainty
22. Ozonesonde Conversion efficiency
23. Integrated Column Ozone and uncertainty [DU]
24. Pressure above which the TCO is calculated [hPa]
25. Ozone residual above (23) and uncertainty [DU]

Uncertainty estimates shall form part of the ozonesonde SGDP collective. GOASS shall be responsible for calculating these estimates addressed in Section 4.7.

4.4.5 File naming convention

The filename convention described here is taken from Section 2.1 of the Manual for the Data Management in GRUAN [GRUAN-TD-1 DRAFT v0.3 (2010-132010-07-13)] and will apply to metadata, CRD, SGDP data files in the designated GRUAN Lead Centres file archive. The obligatory parts of the file names should be:

- Unique Station Identifier → GAW ID and station location name, i.e. NRB_Nairobi_Kenya
- Data level → L2 or L2
- Date / Time of launch → in universal standard time (GMT)
- Data product description → “Metadata”, “CRD” or “SGDP”
- Version of data product → number
- Date / Time of the creation of the file
- Identification of the specific instrument → 'ECCSonde'
- Identification of central tracer → 'Ozone'

An example file is,
NRB_Nairobi_Kenya_20170301T23:50:12_L1_CRD_V1.0.0_20170323T09:01:48_ECCSonde_Ozone.csv

4.4.6 Data format

Metadata, CRD and SGDP will be stored in CSV ASCII format. ASCII format is an accepted standard output used by the leading ozonesonde archiving centers (WOUDC, NDACC, and SHADOZ) and is readily accessible to the global scientific community.

4.4.7 Data dissemination

Users of GRUAN data shall have access not only to the measurements and their uncertainties, but also to the metadata information that includes instrument specifications, operating procedures, data algorithms used, and when changes to any of these occurred through the complete time period of the data set.

4.4.8 Data archiving

- The ozonesonde metadata, CRD and SGDP will be stored at the nominated GRUAN central data processing facility Lead Centre.
- A designated GRUAN storage facility shall be established. This would:
    - Allow the Lead Centre to maintain statistics on data usage. This would be useful when applying for funding to support GRUAN operations.
    - Allow end-users to be informed if and when newer versions of the data become available.
    - Facilitate reporting of potential errors, flags, and anomalies in the data by end-users.
- The metadata and SGDP shall be made available at the NCEI.
- Ozonesonde data dissemination shall comply with the data policy guidelines in Section 8.2 of GCOS-171.
- It is important that the GRUAN archive include all previous versions of any given data set such that analyses using previous versions of data can be repeated if required.

4.4.9 Handling data gaps

GRUAN recognizes that there may be gaps in the profile measurements due to telemetry interference, hardware, and software issues. Profiles shall not be excluded if data gaps occur. There is useful data extending from the surface up to the stratosphere that satisfies the four key user groups of GRUAN data products defined in Section 1.2. Depending on where data gaps occur and the extent of these data gaps, there remains useable quality reference data that can still satisfy one or more of these four communities. Profiles with very large and intermittent data gaps should be identified and evaluated in the annual reports and periodic audits. Ultimately, it is up to the end-user to determine the best use of the data.

4.5. The GRUAN Standard Operating Procedures

GRUAN seeks to ensure that all sites operate to the same reference quality standard to guarantee homogeneity of quality across the network. The WMO/GAW SOP is designed to reduce random errors by maintaining consistent and reproducible ozonesonde measurements. Standardization of the SOP has been shown to improve the precision and accuracy to less than ±5%, while non uniformity in SOP will lead to inhomogeneities in the time series and between station data records [Smit et al, 2007, Deshler et al, 2008].

GRUAN recommends that Ozonesonde Programmes use, at the very minimum, the WMO/GAW ozonesonde conditioning and preparation procedures outlined in detail in Annex A of GAW Report No. 201. GRUAN recommends Programmes adopt of the SHADOZ check list (Appendix A-1) that is rigorous in metadata reporting requirements. It is strongly recommended that potential site candidates use this check list in place their own SOP, but it is not required as long as sites can demonstrate that all metadata found in Appendix A-1 are recorded.

4.5.1 Refurbished Sonde SOP

Refurbished sensors must follow more rigorous conditioning and testing. The ASOPOS panel concluded that at present it is not clear how often recovered ozonesondes can be re-used after reconditioning. Currently there are no quality assurance standards for refurbished sensors and a number of ozonesonde sites fly refurbished sondes using their own set of SOP. Sites risk potentially introducing artifacts in the data records if the re-conditioning procedures are not done properly. A basic set of SOP for refurbished sensors can be found in Appendix A-2, although manufacturer SOP should not be discounted. Further discussion on refurbished sensors can be found in Section 5.5. GRUAN strongly recommends and encourages that JOSIE studies, independent laboratory tests, and inter-comparison field measurements be conducted to establish SOP for refurbished sondes that GRUAN can draw on to incorporate across the Ozonesonde Programme network. Sites that launch refurbished ECC-sensors should follow the NOAA re-conditioning SOP in Appendix A-2 or manufacturer SOP.

4.6. The RSLaunchClient Utility

The RSLaunchClient utility will collect and manage uploaded metadata and ozonesonde CRD to the GRUAN Lead Centre. GRUAN defines essential data as input requirements to the RSLaunchClient. Regarding metadata, GRUAN Ozonesonde Programmes will be required to provide essential metadata, defined in Appendix A.1, to the RSLaunchClient. If one of the basic essential metadata variables is missing a flag will be given or, in some cases, the entire profile will be rejected (e.g. large gaps in metadata reporting or missing key variables in the measurement system that are a component of the SGDP).

Variables specific to the radiosonde data stream, such as P-T-U calibrations, offsets, and uncertainty calculations, shall use the Radiosonde Analysis Software in the GRUAN Radiosonde Technical Document.

4.7. The GRUAN Ozonesonde Analysis Software System (GOASS)

The GRUAN Ozonesonde Analysis Software System (GOASS) is the centralized data processing software that analyzes the CRD of all certified GRUAN Ozonesonde Programmes submitted through the RSLaunchClient utility. Before processing the CRD, the GOASS reconciles the metadata received from the RSLaunchClient with those contained in the GOIMR. Any inconsistency is immediately reported, thus providing a near-real-time check of the measurement traceability and stability, as well as a quick identification of change. The GOASS must be transparent, i.e., must be developed and optimized in consultation with all GRUAN Ozonesonde Programme representatives/investigators, as well as the GRUAN Lead Centre, WG-GRUAN, and TTR. These investigators shall meet regularly to discuss the implementation of updates to the GOASS, and whether processing changes pertain to one or all of the GRUAN

Ozonesonde Programmes. The output of the GOASS consists of certified ozonesonde metadata, CRD, and SGDP.

GOASS must integrate correction methods and associated uncertainties that are accepted by GRUAN and user communities as being appropriate for the science application foreseen. It is therefore the GRUAN Lead Centre, TTR, and GRUAN Ozonesonde Programme Representative's joint responsibility to develop and maintain the operational GOASS. Failure of GRUAN Ozonesonde Programmes to use an operational version of the RSLaunchClient and GOASS will result in delivery delays of the ozonesonde SGDP, and therefore can result in the cancelation of the Programme's certification at the time of its audit.

The GOASS shall perform the following steps to transform the CRD to the final Level 2 GRUAN standard ozonesonde product (SGDP):

1. Apply filtering criteria to test the performance of an individual ECC sensor, summarized in Table 4.7.1 below. Aspects of the conditioning process should fit within the following specific thresholds. GRUAN site operators shall use these threshold criteria to gauge the quality of the ECC sensor and perform repeat tests if necessary to bring the ECC sensor into compliance. Ideally, ozonesonde original data should not be uploaded to the RSLaunchClient if certain threshold criteria are violated.
2. For the case where $IB_{final} > 0.05$ µA GOASS shall recalculate ozone using the minimum of IB0, IB1, and IB2 as IB_{final}. If that minimum background current still exceeds the 0.05 µA threshold then a flag shall be recorded in the metadata. Programmes should specifiy which background current is used as IB_{final}.
3. GOASS shall apply the RH correction, C_{PH}, and C_{PL}, explained in detail in Section 2.4 to calculated the final flow rate, Φ_{Ground}.
4. Radiosonde/Ozonesonde offsets in height and pressure, if any, shall be documented in the metadata and geopotential heights shall be recalculated, in accordance with the GRUAN Radiosonde Technical Document.
5. Adjusted pump temperatures using Equation 2.6.5 and sub-equations shall be calculated.
6. After the above corrections are applied, the ozone partial pressure shall be recalculated using Section 2.1 Equation 1.
7. Uncertainties, covered in Section 3, for each measured parameter in the ozone partial pressure equation shall be calculated as defined by Smit et al. [2012].
8. A total column product shall then be calculated based on the processing protocol defined in Section 2.7.

Table. 4.7.1 Threshold criteria for ECC ozonesondes by the RSLaunchClient to test the performance quality of each sensor. These are specifically for SPC and ENSCI ECC types.

Test Indicator	Threshold Criteria	Action if violated
Average pump flow rate	Within 26-36 sec/ml	Flag and record in metadata
Response Time	20-30 sec	Flag and record in metadata
Pump temperature	273-315 K (-15 – 40 C)	Flag for ozonesonde datum exceeding threshold.
Background I_{B0}	0-0.05 µA	See Section 1.1
Background I_{B1}	0-0.1µA	Flag and record in metadata
Background I_{B2}	0-0.05 µA	Flag and record in metadata
Background I_B	Defined by the site	See Section 1.1
Pump motor current	> 100 µA for SPC, > 90 µA for ENSCI	Flag and record in metadata
Pump pressure	> 10 psi	Flag and record in metadata
Pump vacuum	< 20 in in Hg	Flag and record in metadata
KI Solution	0.5% buffered for ENSCI; 1.0% buffered for SPC; other	Should be always be correct for GRUAN certification. For historic data, where applicable, transfer functions shall be applied.
Pump Correction Factors (PCF)	Komhyr [1986] values for SPC-6A and Komhyr et al. [1995] values for ENSCI	Ozone values shall be recalculated using the correct (PCF)

Flagged Data

Data that are not within threshold levels itemized in Table 4.7.1 shall not be rejected but must be flagged and documented in the final archived metadata. Flagged metadata shall be included as a diagnostic tool in each GRUAN Ozonesonde Programmes annual report. Audits shall use the statistics gathered on flagged metadata and the SGDP to help evaluate the continuity of GRUAN Ozonesonde Programmes.

4.8. GRUAN ozonesonde calibration management

Ozonesonde ground stations generally do not require calibration at the manufacturing, instrumentation, or operational levels. Calibration of the ECC sensor comes from adhering to the SOP and completing the metadata check list requirements. At the time of this document, there is no precedent or standard rules that require sites to test or calibrate aspects of the ground station equipment, nor is there a mechanism to ensure equipment standards and quality. It would ideal to establish guidelines by which a GRUAN Ozonesonde Programme can calibrate its ground station equipment such that sources of error and uncertainty can be further identified, traced, and included as part of the uncertainty budget for ozonesondes.

World Calibration Center for Ozonesondes (WCCOS)

The World Calibration Center for Ozonesondes (WCCOS) at the Forchungszentrum, Jülich, Germany periodically conducts inter-comparison experiments (JOSIE) to establish and maintain quality assurance of the ozonesondes sensors. JOSIE performs routine testing of existing and newly manufactured ECC ozone sensors to (i) check the instrument performance in a controlled environment, (ii) maintain up-to-date SOP, (iii) test individual ECC sensor capabilities, and (iv) develop uncertainty estimates for the individual instrument parameters. The WG-GRUAN shall use findings from the JOSIE reports to evaluate current best practices and whether changes to the ozonesonde SOP or processing procedures are required. Members of the WG-GRUAN are encouraged to participate in JOSIE initiatives to keep abreast of new findings. It is highly desirable for GRUAN sites to endorse and participate in JOSIE-led activities.

Calibration of the ozonizer test unit

The ozonizer used to condition and prepare an ECC sensor does not generate a traceable amount of ozone. Comparisons against an independent calibrated reference, such as a TEI surface ozone monitor, to generate a known ozone amount would be very useful. It is desirable for sites to provide traceable ground/instrument checks, such as a surface ozone monitor (e.g. TEI) at the time of each profile measurement, prior to launch and independent of the manufacturer. In the case of refurbished ECC sensors it is strongly recommended that a calibrated source of ozone to test the instrument performance be used and included as part of their SOP. Ozonesonde programmes shall use digital test units capable of measuring background currents to at least three significant digits. Audits (Section 4.10) shall include the periodic testing of the ozonizers by using a calibrated source of ozone from a reliable instrument. Members of ASOPOS and the TTR+WG-GRUAN shall determine the calibration method and testing.

4.9. Ozonesonde Programme versioning system

A system of traceable version numbers and dates for all GRUAN Ozonesonde Programmes shall be developed to allow for a full identification and tracking of changes in SOP, and data processing since the initial certification. Every reprocessing of the metadata, CRD, and SGDP must be reflected in an increment in the data version and an update to the date of creation by the GOASS (see file naming convention in Section 4.4.5) as prescribed in the data versioning protocols developed by the GRUAN Lead Centre. Such data updates must also be communicated to users who have accessed earlier versions of the data and who have voluntarily registered to receive notifications of such data updates (see Section 8.6 of GCOS-171). For this reason it is also important that all older versions of any data set are always archived and made available through the GRUAN Lead Centre's archive.

4.10. GRUAN Ozonesonde Programme auditing

Certification of GRUAN measurement programmes are not a one-time-only event. GRUAN sites will be audited by members of the WG-GRUAN at 3-4 year intervals to ensure that programmes continues to meet GRUAN standards. The audit will involve:

1. A review of the site’s annual reports.

2. An ozonesonde launch in front of WG-GRUAN auditors that demonstrates that the SOP are being followed in accordance with Section 4.5. (Can be by video for very remote station?)
3. Calibration/testing of the ozonizer.
4. Check lists will be reviewed against the GRUAN Check lists if not used.
5. Discussions with the site representatives responsible for the Ozonesonde Programme.
6. In the eventuality of identified site problems the following protocols shall be followed (taken from Section 5.6 of the GCOS-171):
    1. Should a measurement programme at an existing GRUAN site show significantly reduced observational capability over more than a year, as evaluated by the criteria listed above, the WG-GRUAN and Lead Centre shall investigate the circumstances at that site, and, if needed, exclude that programme from the GRUAN certification for that site. The WG-GRUAN and Lead Centre shall work proactively with sites to resurrect such programmes, providing training, technical and in-kind support as practical and as needed.
    2. Should the overall contribution of a site be deemed sufficiently diminished to call into question its continued presence in the network, the site shall be informed immediately in writing. The site shall be given three months to form a capabilities recovery plan, in consultation with the Lead Centre and WG-GRUAN. Should this plan be accepted the sites should promptly implement agreed key aspects. In the eventuality that this is not achieved, the site shall be suspended with an invitation to submit anew at such a time as problems are remedied.
    3. An existing GRUAN site may also request the temporary suspension of some or all of the measurement programmes at that site from GRUAN certification. This could occur, for example, in cases of unforeseen budget limitations, non-availability of personnel, or some other unavoidable circumstance affecting the measurement programmes at the site. Such a request must be submitted in writing to the WG-GRUAN and the Lead Centre. At some later time, should the site request recertification of their measurement programmes previously suspended, the procedure for certification as outlined in Figure 2 of GCOS-171 shall be followed.

Along with the cooperation and goodwill of participating sites, nations, and individuals, the establishment of these GRUAN site assessment and certification guidelines provides one of the main foundations for ensuring that GRUAN meets its goals as a climate observing network.

5. GRUAN OZONESONDE INSTRUMENTATION

As described in Section 2 (and elsewhere) of the GCOS-171, one key requirement of GRUAN instruments is to provide reference measurements, i.e., using principles based on key concepts in metrology such as (but not limited to) traceability. Traceability must apply at all levels of the data acquisition and processing chain, including instrumentation. An entire ozonesonde system comprises the following components:

1. Electrochemical concentration cell (ECC) ozonesonde which is encased in a molded polystyrene weatherproof box for ascent into the lower stratosphere.
2. Radiosonde.

3. Interface electronics, if applicable, to couple the ECC ozonesonde to the radiosonde.
4. A ground station for receiving data provided by the radiosonde manufacturer. The ground station consists of an antenna, pre-amplifier, and coaxial cable connecting the antenna to a 400-405 MHz receiver.
5. A computer with pre-installed data acquisition and processing software. This allows data to be received and processed during the balloon flight.
6. Software or 1200 baud modem.

Refer to the GRUAN Radiosonde Technical Report for instrument details pertaining to radiosondes and their ground stations and data acquisition systems. Refer to the ECC manuals for information pertaining to the materials and electronics of the ECC sensor mainframe, and type interface circuitry which couples the sensor to the particular type of meteorological radiosonde [e.g. DMT, 2014; SPC, 1999].

The requirements and recommendations on ozonesonde instrumentation provided in this section apply only to the ozonesonde techniques recognized to be mature enough to be providing reference measurements of ECVs of highest-enough priority for GRUAN. As of this Document, these include the SPC and ENSCI instruments:

- Both manufacturer types are considered the leading industry standard for ECC ozonesondes and have a long heritage of launches.
- The commercial demand for SPC and ENSCI is sufficient to support the production and use of the instrument for the expected multi-decade deployment within GRUAN.
- There is no reason to expect that both instrument manufacturers will stop production in the foreseeable future, even if a newer (but not necessarily better) instrument is developed and marketed.
- All ozonesonde stations with long-term ECC records use one or both types and are archived at WOUDC, NDACC or SHADOZ.
- Finally, all WMO-supported ECC inter-comparison studies (JOSIE), campaigns (BESOS) and other laboratory and field studies have included these two manufacturing types. Thus, there is a substantial body of literature documenting their performance and measurement uncertainties.
- Through JOSIE and independent dual-launch studies, the precision and accuracy claims for both instruments and its resultant data is sufficiently robust and meets the uncertainty and stability standards under Section 4.1 of GCOS-171.

Radiosonde and ground station data acquisition system packages shall be assessed through the TTR to ensure compliance with GRUAN measurement standards. It is important to note that GRUAN shall not prescribe any instrumentation system and setup in particular. Rather, GRUAN shall provide simple and practical recommendations that encourage sites to use the best practices in full compliance with the requirements and recommendations detailed in this Guide.

GRUAN recognizes that ECC sensor technology is constantly evolving and that not all sites within GRUAN will operate the same ECC sensor, e.g. a new site may decide to adopt a new ECC-sensor that has not been yet been included in JOSIE studies, or an existing site may continue to use an older manufacturing model or obsolete sensing solution (e.g. 2% unbuffered) to avoid potentially introducing a discontinuity in the measurement time series. That said, the fewer the number of different types of instruments and measurement techniques deployed within and among GRUAN Ozonesonde Programmes, the more likely network homogeneity will be achieved.

In the event that a new ECC ozone sensor is commercially developed, GRUAN expects the manufacturer to (i) actively participate in JOSIE and other instrument inter-comparisons, (ii) be willing to disclose the necessary information required to form a fully traceable chain of sources of measurement uncertainty in accordance with the GCOS-171 mandatory operating requirements, and (iii) make available the algorithms used for corrections within the data processing software to conduct uncertainty analysis. In accordance with GCOS-171 guidelines, it is a 'fundamental requirement that the information required to reprocess the data at any time in the future must be made available (though not necessarily publicly available)'.

5.1. The SCIENCE PUMP CORPORATION ozonesonde

The earliest Science Pump Corporation (SPC) ECC ozonesonde measurements occurred in the late 1960's [Komhyr, 1969]. Table 1 from Johnson et al. [2002] summarizes the model production dates and design changes from the earliest SPC design (SPC-1A). The first known operating guidelines for preparing ozonesondes for flight was created for the now retired SPC-4A model in the NOAA technical memorandum [Komhyr, 1986]. The current manual has been optimized for the SPC-6A model design [SPC Manual, 1999].

GRUAN protocol procedure

As of this document, the GOASS shall process CRD from SPC-4A models and higher to produce the ozonesonde SGDP using procedure protocols established in this document. All other historic SPC profiles from older SPC models should be inventoried and properly conserved until such time as their information content can be evaluated, assessed, and assigned uncertainty estimates that conform to GRUAN reference standards and guidelines.

While the SPC modifications over time improved ECC performance, error characterization in models older than SPC-4A are not as well known. The first SOP manual was conceived with the SPC-4A model design in mind and changed with model design as they were altered to optimize performance. Given that these older SPC models no longer exist and are no longer flown, JOSIE-type studies or campaigns are necessary to determine error estimates or empirical corrections to all historic instrumental parameters.

5.2. The ENSCI ozonesonde

ENSCI Corporation started in the mid 1990's with similar ECC sensor instrument configuration to that of the SPC-5A model (refer to Table 1 of Johnson et al., [2002]). Komhyr [1997] published the first ENSCI operations handbook for the 2Z model. There is no significant instrumental differences between the Z and 2Z models [Bryan Johnson/NOAA, personal communication]. The Z model is configured to be compatible with interface boards of other ground station systems (e.g. Vaisala) while the 2Z has a built-in V7 interface board compatible with the iMET ground station. Since the late 2000's Droplet Measurement Technologies (DMT) took over the manufacturing of ENSCI ECCs. The model design has remained unaltered at the helm of DMT, thus GRUAN does not make a distinction between the two companies. As of this document, the most up to date ENSCI manual has been published by DMT [2014] and includes much of the WMO/GAW SOP recommendations and protocols. In 2015 ENSCI has separated from DMT and is once again it's own manufacturing entity.

GRUAN protocol procedure

The GRUAN archive shall accept ENSCI Z, 2Z ozonesonde instrument profiles to produce the ozonesonde SGDP.

5.3. Measurement Redundancy

> "Having different instruments at GRUAN sites measuring the same atmospheric parameters will be invaluable for identifying, understanding and reducing systematic effects in measurements"
>
> \- GCOS-171

Examples of redundant instruments that measure profile ozone are the ozone Lidar and Microwave Radiometer. Other ozone monitoring instruments to consider that can complement ozonesonde profile measurements are the TEI surface ozone monitor and UV Vis instrumentation. All these instruments can provide uninterrupted hours of measurements at one given location. Unlike these fixed located instruments, balloon-borne ozonesondes provide in-situ measurements at varying locations and altitudes with time. The challenge therefore is to match the ozonesonde altitude and time with those other instruments with careful considerations about the geographic displacement from the ground-based instrument site. Section 6.4.2 in GCOS-171 provides an overview of the characteristics of Lidar and microwave instrumentation. Methods on resolving the time/altitude differences from these instruments shall draw on information found in the GRUAN technical documents for Lidar and Microwave Radiometers. GRUAN shall draw on methods developed by Calisesi et al. [2005], Bodeker et al. [2013], Hassler et al., [2008] and references therein, that create site atmospheric state best estimates (SASBE) of ozone profiles from combining ozone instrumentation of varying temporal and spatial resolutions to provide objective evaluation of ozonesonde performance. Ozonesonde measurements themselves may be part of SASBE.

5.4. A typical GRUAN ozonesonde data acquisition system

The ozonesonde is interfaced with a radiosonde and uses its data acquisition system to transmit and record the ozone cell current and other parameters used to calculate the ozone partial pressure (see Equation 1 in Section 2.1). The ozonesonde/radiosonde equipment and data acquisition system shall also be referred to as the 'ozonesonde ground station'. From to Section 6.1 of GCOS-171

> "GRUAN will not prescribe the use of specific instruments in the network since the emphasis is not on prescribing an instrument, but rather on prescribing the capabilities required of an instrument and allowing individual sites to select an instrument that achieves those capabilities."

As of this Document, there are a number of ozonesonde/radiosonde ground station systems operating with varying degree of publicly available documentation. These include Vaisala (Finland), iMET (USA), Lockheed-Martin-Sippican (LMS, USA), Meisei (Japan), Modem (France), GRAW (Germany), and ChangFeng (China). The Vaisala type ground station system is the most commonly used, having a heritage of long-term records of ozonesonde and radiosonde measurements. Specific to radiosondes there is a large body of literature that have characterized the uncertainties and biases among the Vaisala models (Dirksen et al., [2014] and references therein; Hurst et al. [2011]; Nash et al. [2006; 2011]; Steinbrecht et al., [2008] and references therein; and Vömel et al. [2007]). Hurst et al. [2011] and Stauffer et al [2014] were among the first inter-comparison studies of iMET and Vaisala models. Both iMET and Vaisala adhere to the instrument selection requirements addressed in Section 6.1 in GCOS-171. This includes, but is not limited to, information content, instrument heritage (e.g., maturity), sustainability (e.g. sufficient commercial demand), robustness of measurement uncertainty, and manufacturer support. Both ozonesonde ground station systems are known to provide all the essential raw data and metadata.

As of this Document, there is varying degree of documentation that is publicly available on the other ozonesonde/radiosonde ground station systems mentioned above. However, meeting the GCOS-171 instrument selection criteria and GRUAN data quality assurance and measurement standard policies can be assured provided that the manufacturer is:

- Willing to provide essential CRD and metadata to generate the SGDP.
- Prepared to actively participate in instrument inter-comparisons (e.g. JOSIE) and field campaigns (e.g. BESOS).
- Willing to disclose the necessary information required to form a fully traceable chain of sources of measurement uncertainty (e.g. releasing SOP and algorithms used for any corrections within its data processing software).

GRUAN procedure protocol

1. GRUAN requires that candidate sites use ground stations that provide the essential metadata (see Appendix A.1) and CRD necessary to generate SGDP (see Table 4.1).
2. GRUAN shall encourage all ozonesonde/radiosonde ground station manufacturers to participate in JOSIE-led and other WMO-sponsored intercomparison activities.
3. GRUAN shall encourage ozonesonde/radiosonde ground station manufacturers to provide documentation on laboratory and/or dual sonde launches to demonstrate that the precision and accuracy fits within ±(3-4)% and ±(4-5)% of the JOSIE results, respectively. These results have been determined by Smit et al. [2000] using the leading SPC and ENSCI ECC sensors in chamber experiments.

5.5. Refurbished Ozonesondes

The ASOPOS panel concluded that at present it is not clear how often recovered ozonesondes can be re-used after reconditioning. The general recommendation by the ASOPOS panel is not to fly re-used ECC-sondes. However, for a number of ozonesonde sites it is the most cost-effective way to ensure financial stability of their programme and maintain their ozonesonde launch schedule. GRUAN shall (i) encourage sites at unique locations (refer to Section 4.2.1 on added-value criteria) that regularly launch re-used sondes to apply to become a GRUAN site and (ii) not prohibit existing Ozonesonde Programmes from including data from refurbished ozonesondes, provided that all operating conditions set forth by this Document are met.

Refurbished sensors falls under one of the “9 items” under managing changes in Section 7 of this report. Thus, established GRUAN Ozonesonde Programmes that wish to include refurbished sensors falls under the guidelines of a “change event” and programmes shall follow steps in Section 7.1 to include refurbished ozonesondes into their programme. For new candidate sites seeking to become a GRUAN site this information should be included as part of their GOIMR.

For individual GRUAN Ozonesonde Programmes re-using ECC-sensors, the re-conditioning SOP of recovered sondes should be done by trained personnel in such a way that the resulting metadata is always within the threshold criteria defined in Table 4.5. For refurbished ozonesondes it is recommended that Ozonesonde Programmes following the modified NOAA prescribed re-conditioning instructions found in Appendix A-2 or re-conditioning procedures as given by the sensor-specific manufacturer.

In recognition of the heterogeneity of the GRUAN ozonesonde network, the WG-GRUAN and GRUAN Lead Centre shall evaluate individual candidate sites ability to launch refurbished sondes based on the following:

- GRUAN Ozonesonde Programme applicants will first be assessed according to their ability to meet the mandatory operating protocols defined in Section 5.3 of GCOS-171 and specifically 4.1 of this report, and then according to the added value they bring to the network, as defined in Section 4.2.1 of this Document. This will enable candidate sites to operate their ozonesonde programme to GRUAN standards.
- Consideration shall be given to, but not be limited to, the following:
    - Historical data – sites with long term homogenous data records is a desirable factor.
    - Operation set-up.
    - The ability and skill of site operators to re-condition sensors following re-conditioning operating protocols (Appendix A-2 or manufacturer specific).
    - Funding constraints.
    - The launch schedule, which is a defining factor in assessing the extent to which the candidate site can become a fully operational GRUAN Ozonesonde Programme.

Candidate sites must clearly demonstrate that each refurbished ozonesonde is measuring ozone with an accuracy and uncertainty similar to that of a new ozonesonde. This can be done using calibrated ozone instrumentation, e.g. a TEI ozone photometer, that tests the sensor performance against known quantities of ozone, and through dual sonde inter-comparisons.

6. OZONESONDE MEASUREMENT SCHEDULING

As detailed in Section 5.2.1 of GCOS-171, a fully equipped GRUAN site is required to make weekly ozone profile measurements. While it is not stipulated whether such measurements should be made using ozonesondes, lidar or microwave radiometer, the expectation is that an ozonesonde measurement programme would be a fundamental part of a GRUAN vertical ozone profile measurement programme.

Scientifically, measurement scheduling for GRUAN ozonesonde programmes is likely to be driven by:

- The needs of the stratospheric ozone change detection community. Ozonesonde flights need to be made sufficiently frequently to provide ozone time series suitable for detecting trends in the vertical distribution of ozone.
- The needs of the air quality assessment community. Because ozone is a component of urban air quality, ozonesonde measurements need to be made sufficiently frequently to support air quality process studies.
- The needs of the satellite validation community. To the extent possible ozonesonde launches should be timed to coincide with overpasses of satellite which are also making measurements of the vertical profile of ozone.

Ozonesonde protocols will continue to develop over time and, in the case of conflict between GCOS-171 guidelines and this Ozonesonde Technical Document, the schedule outlined in this Document shall take precedence (see Section 7.5 of GCOS-171).

Measurement scheduling for GRUAN ozonesondes is driven by one main factor: financial support for expendables which include the ozonesonde sensor, solutions, interface electronics, and the balloon payload. Once an ozonesonde is launched it is typically irretrievable. It is not common for sites to retrieve, re-condition, and re-launch the same sensor. Geography, land restrictions, weather, and additional resources can prohibit such rescue attempts. Schedules will depend upon available expendables and so there cannot be a proscriptive solution. GRUAN shall adopt the following schedule guidelines:

- In seeking a practical balance between sites with funding constraints and GRUAN scientific goals, GRUAN shall accept a minimum requirement of two times per month launches to be spaced every other week. Candidate GRUAN ozonesonde programme sites shall first be assessed according to their ability to meet the mandatory operating protocols defined in Section 5.3 of GCOS-171 and then according to the added value they bring to the network, as defined in Section 4.2.1.

- A fully equipped GRUAN ozonesonde programme shall make weekly launches. If and when possible, GRUAN shall encourage candidate or newly certified sites to become a fully equipped GRUAN site.

- Sites shall be expected to, in good faith, upload metadata and CRD to the RSLaunchClient utility as soon as the launch is complete and that site has successfully archived their metadata and CRD.

- Sites shall commit to launching at around the same time of day. This is to maintain the representativeness and homogeneity of the data record. Variable launch times may affect the accuracy of trend assessments [Thompson et al., 2014].

- To the extent possible, launches should be timed to coincide with satellite overpass times that measure total column ozone and/or vertical profiles of ozone.

- Weather permitting; GRUAN advises launching the same day for bi-monthly to weekly sounding schedules. Altering a planned launch date due to inclement weather such as a natural disaster, strong winds, heavy rains, and storms that would impede a successful launch is expected. Altered scheduled launches shall be included as part of the annual report summaries.
- Where possible, measurement schedules for redundant systems should be synchronized so as to avoid sampling biases when combining the measurements into a single data product.
- Measurement scheduling shall remain stable unless there is a clear requirement for change, which would then have to be agreed with the relevant GRUAN sites. Amendments to the GRUAN measurement scheduling protocol shall follow guidelines outlined in Section 7.1 of this report.

When laboratory studies and dual ozonesonde launches are proposed, the regular launch schedule must not be interrupted.

6.1. General considerations from Section 7 of the GRUAN Guide

The candidate site shall work with the WG-GRUAN and TTR to define a measurement schedule that allow the resultant ozone data products to best capture all important scales of temporal variability, both for trend analysis and for process understanding.

In designing the Ozonesonde Programmes measurement schedule it will be necessary for the TTR and WG-GRUAN to work closely with individual sites since scheduling will be site specific. For example, some sites are more likely to (i) experience specific or unique atmospheric conditions related to the understanding of associated processes compared to other sites, (ii) be more financially constrained compared to other sites, and (iii) experience limit operating capabilities compared to other sites.

Given that task teams have a finite operating life, should the TTR no longer exist, this scheduling guidance responsibility shall fall to selected members of the WG-GRUAN who may include participants from the wider GRUAN community to assist with revising measurement scheduling protocols.

7. MANAGING CHANGES

Changes in instrumentation, operating procedures, and data processing algorithms are likely to introduce sources of operational uncertainty into the ozone profiles measured within GRUAN Ozonesonde Programmes. The primary goals are to (i) avoid unnecessary changes, i.e. those changes that have no scientific, financial or operational benefit, and (ii) where changes are beneficial and/or necessary, to manage those changes in a way that the homogeneity of the ozonesonde data record is maintained across the transition and that the change does not compromise the integrity of the long-term record.

Ozonesondes have gone through several modifications since they were first introduced in the 1960s and there is no reason to believe that those modifications will cease. Without such modifications there would be no opportunity to improve the performance of the instruments. Therefore, while GRUAN encourages ozonesonde manufacturers to improve the performance of the instruments, GRUAN also recognizes that managing such changes in instrument design or function is essential for maintaining long-term stability of the ozonesonde data products.

Factors influencing trends in an ozonesonde dataset to consider include the following changes (termed as "9 items" hereinafter):

1. SOP
2. GOASS data processing algorithms
3. ECC-sensor
4. Solution concentration
5. Location of launch site
6. Operating environment of the ozonesonde
7. Ground station system
8. Radiosonde manufacturer
9. Inclusion of refurbished ECC-sensors

These are all likely to introduce inhomogeneities into ozonesonde SGDP time series. This section describes the protocols for managing changes for a GRUAN Ozonesonde Programme. This section is developed based on the section "Managing change" of the GCOS-171 GRUAN Guideline.

7.1. Change Event Notification

A change event begins with the start of change of any one of the above "9 items". The impact of new ozonesonde systems or changes to existing systems should be assessed by GRUAN prior to archiving with a suitable period of overlap between new and old items. This will be dictated by the GCOS-171 guidelines and is addressed further in Section 7.7. GRUAN recognizes that regular operations will continue regardless of GRUAN's official acceptance.

- The GRUAN site, in writing, shall first issue a change event notification to the GRUAN Lead Centre.
- The Lead Centre, a GRUAN Ozonesonde Programme, an ozonesonde instrument manufacturer, or another member of the GRUAN community may also initiate a proposal for changes.
- The Lead Centre must act as a clearinghouse for all proposed changes to (a) assure high stability and (b) decide when an improvement merits a change to the GRUAN ozonesonde procedures.
    - The Lead Centre, in consultation with ozonesonde experts, makes an initial evaluation of the proposed change.
    - If considered to be worth pursuing, the Lead Centre assesses the advantages, disadvantages, and potential impacts of the proposed change.

- *Justification of change*: Any change to the "9 items" in a GRUAN Ozonesonde Programme must be fully justified before the change is enacted. An assessment report must be submitted in which advantages and disadvantages of making the change must be carefully assessed. Laboratory tests of old and new items, if relevant, should be included in the assessment report. Any relevant results in the peer-reviewed literature should be included in any change assessment.

- The information and data required to manage the change are captured in a "change evaluation report" that will become a key component of the metadata associated with the change.

- *Preparing for change*: the Lead Centre must undertake a quantitative assessment of the impacts of any planned change before the GRUAN GOASS implements the change.
  - The assessment must cover a sufficient period of time, not just the change period.
  - Some changes have already been anticipated and assessed in this Document with a change implementation process as part of the GOASS (e.g. changing from SPC to ENSCI, or changing solution strength (See Section 7.2)).
  - If additional laboratory studies or dual ozonesonde launches are required, such studies must be undertaken by with participation by the GRUAN site representatives and identified ozonesonde experts.

- A change event ends with the official acceptance of the change that has been made after a careful and rigorous assessment.

7.2. Guiding Principles?

The impact on the ozonesonde SGDP product and its uncertainty needs to be assessed in such a way that

1. knowledge of the newly changed item is at least as detailed as knowledge of the old one.
2. Tests are, or have been, conducted (e.g. processing a large number of common datasets by both new and old algorithms if a change in algorithm is proposed).
3. The resulting ozonesonde SGDP after the change are either unchanged or an improvement in terms of continuity, accuracy or integrity. If a considerable improvement in one aspect (e.g. accuracy) is gained, at the cost of a slight degradation of the other aspects, it might be still justifiable to propose a change.

If the GRUAN Ozonesonde Programme decides to proceed and implement the change, any data and metadata collected as part of the change process must be recorded in the metadata submitted to the RSLaunchClient utility. This information will then be archived as part of that programme's metadata record in the designated GRUAN archive.

Validating impacts: No discontinuities in the measurement series or schedule should occur if a change has been properly managed. This is done through the *justification* and *preparing for change* items in Section 7.1. Validation of the process can be achieved by subjecting the entire measurement series to homogenization tests, or may require a reprocessing of historical data. Impacts of changes must be assessed in light of the different intended uses of the SGDP.

Change and uncertainty: Knowledge of an ozonesonde measurement system can never be complete or perfect. Transitioning from an old to a new measurement system always introduces an additional source of uncertainty that must be captured in the uncertainty estimate on the measurements.

Supporting reprocessing: As new and more in-depth knowledge of ozonesonde instrumentation and processing is gained, reprocessing of historical data may be necessary. Such reprocessing may require revision of the homogenization procedures. It is essential, therefore, that original CRD data, as was well as detailed metadata collected during change events, are archived so that such reprocessing can be done with minimal impact to the measurement accuracy.

Single change requirement: Whenever a measurement system is changed, as many similarities as possible between the old and new systems should be maintained e.g. both the ozonesonde and ground-station should not be simultaneously changed. Multiple simultaneous changes must be avoided so that the quantitative assessment of the impact of the change on the measurement and its uncertainty is not confounded with other simultaneous changes.

Monitoring changes: Most changes are planned and therefore can be managed. However, some changes may be unplanned (e.g. natural disaster, changes in funding). Under these circumstances, a GRUAN Ozonesonde Programme shall be placed on hold until the site can be re-established. It may be that re-certification is required. This shall be determined by a site visit from members of the Lead Centre (see Section 4.2).

Use of independent, redundant measurements: Redundancy in ozone measurement systems provides a powerful tool for validating the management of changes to the ozonesonde system. To take advantage of measurement system redundancy, it is essential that these independent systems are not changed simultaneously.

Manufacturer involvement: Efforts must be undertaken to avoid unknown changes e.g. the instrument manufacturer making unannounced changes. GRUAN needs to establish close working relationships with instrument manufacturers so that any changes implemented in the manufacturing of an instrument are made know to the GRUAN ozonesonde community.

7.3. Managing changes in instrumentation

Efforts must be undertaken to avoid unknown instrument changes e.g. the instrument manufacturer making unannounced changes to the material or configuration of the ECC sensor, or a ground station software update. Late response to changes or upgrade announcements may result in discrepancies in the measurement time series. One way to ensure that instrument changes are identified, characterized, and recorded such that there is no discontinuity in the network, as a whole, is for mandatory GRUAN representation at future JOSIE and other collaborative intercomparison studies. This will not only safeguard the homogeneity of datasets due to instrumentation changes but will also ensure that GRUAN (1) follows retractions or addenda to the original GAW Report No. 201 recommendations and SOP protocols, (2) be informed of changes in manufacturer design and materials, and how these affect ozonesonde performance, (3) be aware of changes in the processing software, and (4) be advised of additional concerns in the SOP.

GRUAN Lead Centre needs to establish close working relationships with ozonesonde instrument manufacturers (e.g. SPC and ENSCI) and ozonesonde/radiosonde ground station manufacturers (e.g. Vaisala, Modem, Chang Feng, etc) so that any changes to be implemented or having been implemented are known to them. Preferably the changes can be known substantially in advance of deployment, allowing sufficient time to investigate, understand, prepare for and document the change and its likely impacts.

7.4. Managing changes in SOP and operating environment

Currently, there are multiple variations in ozonesonde preparation procedures since the first manual was written [Komhyr, 1986]. Besides modifications in the manufacturer's instructions in past the decades, scientific institutions have established their own modified operating procedures. There are also a number of ozonesonde processing software systems that apply their own treatment of the variables that go into Equation 1. Smit et al., [2007] reports that maintaining SOP improves the precision of the overall measurements better than ±3-5%. GRUAN recommends that each station maintain the GRUAN Lead Centre certified set SOP for pre-flight and day of flight conditioning established by WMO/GAW to ensure consistency and homogeneity in operating practices. The goal here is not to disrupt the continuity of the long-term practices.

As described in Section 4.5, while implementing these SOP is not mandatory, sites are required to document where they have deviated from the GRUAN certified SOP and, when audited, are assessed for their ability and willingness to adhere to the SOP within GRUAN.

Some changes in the operating environment may be unplanned, such as in the event of a natural disaster, erosion of the field site or land-use changes that necessitates moving the operating environment. Under these circumstances, a GRUAN Ozonesonde Programme shall be placed on hold until the physical site can be re-established. It may be that the new location is far enough away from the original location that a new GRUAN site needs to be established in place of the old site. The task team assigned by the Lead Centre shall determine this. In this case, re-certification will be required because the new location and operating conditions will need to be re-assessed. The process of re-certification shall follow the guidelines addressed in Section 4.2. In their annual report, each site shall document any changes to their current certified SOP and operating environment and include (1) why those changes occurred, (2) how those changes were managed, and (3) the impact, if any, on the homogeneity, accuracy, and integrity of their measurements.

GRUAN sites shall follow the change protocol outlined in Section 7.1 if changes to items (1) and (6) of the "9 items" occur.

7.5. Managing changes in data processing algorithms

As in any data processing situation, there will be occasional re-processing of the ozonesonde CRD after updates/upgrades of the GRUAN GOASS, addressed in Section 4.7. The GOASS must be transparent, i.e., developed and optimized in consultation with WG-GRUAN members. WG-GRUAN shall meet regularly to discuss the implementation of updates to the GOASS, whether they pertain to one site or the entire ozonesonde network. Planned changes in data processing algorithms should be dealt with in a fashion similar to planned changes in SOP.

Changes in the GOASS may be due to:

1. New or modified transfer functions
2. Updated uncertainty calculations
3. Changes in the pump efficiency factors
4. Changes in the partial ozone column calculation above balloon burst
5. Changes in the metadata reporting

These changes will likely result in the complete reprocessing of entire data sets across the network. Since there is a time and administrative cost associated with the reprocessing of a record, such reprocessing should only be undertaken when justified.

Traceability is a leading component of GRUAN. Every single GOASS update must be associated with an increment of the data processing version. A system of traceable version numbers for all ozonesonde level products shall be developed to allow for a full identification and tracking of the data processing changes made since the initial product delivery. The Lead Centre task team shall determine this product versioning system (see Section 4.9).

Data processing updates must be communicated to users who have accessed earlier versions of the data and who have voluntarily registered to receive notifications of such data updates (see Section 8.6 of the GRUAN Guide). Therefore, all older product versions must be made available through the GRUAN archives.

7.6. Managing changes in calibration

When ozonesondes are calibrated to fundamental calibration standards (e.g. SOP) as part of the pre-flight ground-check, changes in sonde performance can be more easily managed. If possible, the impacts of a change in calibration should be quantified through traceability of the calibration standard. For example, the WCCOS in JOSIE studies satisfies the protocols for maintaining ozonesonde continuity, accuracy and integrity through periodic quality checks of instrumental performance of ozonesonde from different manufacturers, and establishing up-to-date SOP. It would ideal to establish guidelines by which a GRUAN Ozonesonde Programme can calibrate its ground station equipment such that sources of error and uncertainty can be further identified, traced, and included as part of the uncertainty budget for ozonesondes. Metadata also provides a traceable source from which a change in the essential characteristics of each unique ozonesonde sensor can be identified, measured, and recorded.

7.7. Validating changes using parallel observations

Cases where parallel observations are applicable to the ozonesonde programme are the following (hereafter called "4 cases"):

1. A new ECC sensor is developed
2. A new sensing solution recipe is developed
3. Change in SOP
4. Change in radiosonde manufacturer and/or model

If any of the above changes occur, a combination of JOSIE studies, other laboratory inter-comparisons, and dual sonde launches must be made to establish (1) new precision and accuracy estimates, if any, (2) changes in uncertainties, and (3) new transfer functions to maintain homogeneity within a time series of a single site and within the network. While these studies are proposed and conducted, the regular observations schedule must not be interrupted. In the case when laboratory studies cannot be reconciled, this must be noted as part of the metadata. In this case, a proposal of how to resolve the discrepancy should be developed by the Lead Centre or a task force commissioned by the Lead Centre.

Measurement redundancy: Measurement redundancy (see Section 6.2 of GCOS-171) highlights the benefits for managing instrumentation change. If parallel observations of the above four changes are not feasible, the availability of additional redundant measurements with similar sampling attributes (vertical resolution, temporal sampling frequency etc.) is essential for validating a managed change.

Inter-comparisons: Formal measurement inter-comparisons, in the form of dual or multi-payload ozonesonde launches are essential for developing the in depth understanding required to manage changes in the "4 cases". For this reason, participation in inter-comparison compaigns is expected. Outcomes from such inter-comparisons must form an important component of the metadata archived at the GRUAN Lead Centre. GRUAN Ozonesonde Programme should participate in, or leverage from WMO and partner networks (e.g. SHADOZ and NDACC) instrument inter-comparison campaigns.

7.8. Implementation of Network-wide changes

Considering the critical importance of change management and that GRUAN sites should not act unilaterally in implementing changes without informing the GRUAN Lead Centre, a procedure for implementing network-wide changes has been described in Section 2.3.11 of the GRUAN Guide to Operations.

The Lead Centre should consult with ozonesonde experts (e.g. members of the ASOPOS panel), science experts from the four key user communities, and other ozonesonde archive centres such as SHADOZ and NDACC to thoroughly evaluate the potential implications of network wide implementation of the proposed change. If the proposed change is approved, the Lead Centre, in consultation with the nominated central processing facility, will develop a formal change plan for implementation across the network. The formal change plan is then communicated to all GRUAN Ozonesonde Programmes within the network.

7.9. Data and metadata traceability

It is essential that metadata capture information regarding any change events (see Section 7.1). Metadata must tie the new SGDP via a comparable traceability chain, back to the same recognized standard as the old SGDP. Detailed archiving of instrument metadata will be vital to managing changes in instrumentation.

Storage: It is essential that digital storage of metadata and CRD be maintained at each GRUAN site. Each Ozonesonde Programme's data storage policy shall be evaluated by the WG-GRUAN as part of the site assessment and certification process (Section 4.2), and re-evaluated in audits and annual reports.

Metadata changes from the GRUAN check list: As described in Section 4.6, while using the GRUAN check list is not mandatory, sites are required to document where they have deviated from the prescribed check list and, when audited, are assessed for their ability and willingness to adhere to them within GRUAN.

8. Quality Management

This section defines the principles and framework for GRUAN operations, and details how activities will be coordinated to manage and control data quality within GRUAN. This section draws heavily from Section 10 of GCOS-171 and reiterates much of the data management policies central to all GRUAN measurement programmes.

Quality management is required at all points in the measurement process from network planning and training, through installation and site operations, to data transmission and archiving. Quality management within GRUAN consists of quality assurance and quality control:

Quality assurance (QA): The purpose of quality assurance is to provide confidence that the requirements for achieving quality are fulfilled. QA includes all the planned and systematic activities that will be implemented such that quality requirements for a product or service are fulfilled.

Quality control (QC): The purpose of quality control is to ensure that the expectations created by QA are fulfilled. QC is associated with those operational methods, techniques and activities used to ensure that the quality requirements (as defined by QA) are fulfilled.

The GRUAN quality management policy is to achieve a level of data quality that allows the primary goals of GRUAN to be met for all potential users of GRUAN data products. QA and QC are both required at all stages of the GRUAN ozonesonde data production. Because SGDP are intended to be used for long-term trend detection, quality assurance and control are further extended to data re-processing (addressed in Section 7 of this Document).

Methods by which QA for Ozonesonde Programmes can be achieved is through the following:

1. The use of redundant measurements, as described in Section 5.3, serves to assure the quality of the GRUAN data products. Agreement of two independent measurements (e.g.

Lidar and Microwave Radiometer), preferably based on different measurement principles, provides a high degree of confidence that no significant systematic effect was disregarded and uncertainties were not under-estimated.

2. Laboratory tests are fundamental methods for establishing and confirming uncertainty estimates and transfer functions for GRUAN data products. Laboratory tests provide an opportunity to investigate, in detail, the performance of instruments under controlled conditions and to measure differences against certified references or other standards (e.g. JOSIE). Data from these experiments can be used to detect biases that may be corrected for and to determine calibration uncertainties.

3. Field inter-comparisons (dual or multi sonde launches on a single payload) allow multiple in-situ sensors to be directly compared under the actual atmospheric conditions of the required measurement, including the complex environmental conditions (temperature, humidity, pressure, wind/flow rate, radiation, and chemical composition) that cannot be fully reproduced in the laboratory. These complementary activities increase confidence that measurements are subject to neither unanticipated effects nor undiscovered systematic uncertainties. Therefore field experiments are particularly useful for assuring the quality of GRUAN data products.

QC will be achieved through the application of the various measurement protocols defined in this Document and in related measurement system documents (e.g. Lidar, Radiosonde technical documents). To the extent possible, visual inspection of all data by science/instrument experts will be required for ozonesondes to minimize anomalies that slip through automated routines. The Lead Centre shall coordinate this effort, which shall be distributed across different GRUAN sites and other interested parties as deemed appropriate including task teams and members of WG-GRUAN. Uncertainty estimates covered in Section 3 of this Document will be used as a metric to compare the site-to-site quality of the observations.

A key aspect of quality management within GRUAN will be fulfilling customer requirements. To this end, systems shall be developed to:

1. Inform users of GRUAN products of site-specific or network-wide changes in measurements systems.
2. Provide an incident reporting system that can flag data anomalies to users.
3. Inform users of updates to previously accessed data products.
4. Provide “help desk” support to users of GRUAN data products.

8.1. Assuring the quality of GRUAN Ozonesonde Programmes

Ozonesonde sites vary in levels of maturity (length of operation), resource (launch frequency), and possess varying levels of infrastructure (air-conditioned versus ambient laboratory conditions) and financial support (piecemeal, intermittent, or stable funding). The purpose of quality management is to ensure that GRUAN data meet the requirements in terms of uncertainty, resolution, continuity, homogeneity, representativeness, and timeliness for their intended use.

Five critical components are required to assure the long-term quality of GRUAN Ozonesonde Programmes:

1. Maintaining consistent, up-to-date SOP to minimize systematic errors and lend confidence in the observed trends.
2. GRUAN-specific training of the representative and ozonesonde technicians of candidate ozonesonde sites, the purpose of which is to ensure that the latest GRUAN-recommended best practices for ozonesonde operations are observed.
3. The RSLaunchClient utility, the purpose of which is to upload, the raw measurement data and metadata to the GRUAN central ozonesonde data processing facility.
4. The GOASS, the purpose of which is to analyze, in a consistent manner, the CRD and to generate the ozonesonde SGDP.
5. Maintaining documentation and statistics on flagged metadata and data and significant data gaps are to be used as a diagnostic tool as part of the quality control assessment and to ensure the continuity of individual GRUAN Ozonesonde Programmes.

Routine testing through intercomparison peer-reviewed studies of new ECC models, changes in instrument design, or solution recipes will help to ensure confidence in observed trends in the future. Therefore, as part of the QA for ozonesondes that are in routine use, GRUAN shall follow protocols established by the Forschungszentrum Jülich that houses the World Calibration Center for Ozone Sondes (WCCOS). The simulation facility enables control of pressure, temperature and ozone concentration and can simulate flight conditions of ozone soundings up to an altitude of 35 km, whereby a UV photometer serves as a reference [Smit et al., 1998]. The long-term objective of WCCOS is to ensure thee major QA-tasks:

1. QA-Procedures: Establishment and up-date of SOP of different sonde types.
2. QA-Manufacturers: Performance check of ozonesondes from different manufacturers.
3. QA-Operation: Evaluation of ozonesonde operating practice of difference sounding laboratories.

8.2. Ozonesonde data product validation

Quality control at the CRD level is performed in two steps, first through uploads of the original data and associated metadata through the RSLaunchClient utility, then through the threshold quality checks at the early processing stage of the GOASS (selection criteria are addressed in Table 4.7.1 in Section 4.7). The suitability check of the CRD and metadata to be accepted as part of the GOASS processed stream serves as a means to verify the completeness of the information required by the RSLaunchClient.

Ozone profiles from GRUAN Ozonesonde Programmes will, in the first instance, be validated against available redundant ozone profile measurements made at GRUAN sites. Multiple measurements of ozone will be invaluable for identifying, understanding and reducing systematic effects in ozonesonde measurements. The cross-checking of redundant measurements for consistency should be an essential part of the GRUAN quality assurance procedures. Since all data are to be reported with uncertainties, a consistency check should, in principle, be a straightforward task.

Satellite-based measurements of total column ozone (e.g. OMI, GOME-2, TROPOMI) and profiles of ozone in the lower stratosphere (e.g. Aura/MLS, SAGE III) are common reference measurements that can be used to assess the quality of ozonesonde observations. GRUAN shall, where practical, schedule ozonesonde launches in near real-time (i.e. within 2 hours of a satellite overpass) to fulfill the requirement of providing a reference to satellite measurements.

In addition, GRUAN Ozonesonde Programmes are encouraged to participate in field campaigns that include measurements from an independent instrument, i.e. UV photometer. If two measurements are known to be dependent, the degree of this dependence as well as its consequences must be specifically described and taken into account in the product assessment. As stated in Section 10 of the GCOS-171, “Agreement of two independent measurements, preferably based on different measurement principles, provides a high degree of confidence that no significant systematic effect was disregarded and uncertainties were not underestimated”.

8.3. Performance monitoring system

Applying the principles described in Section 10 of the GCOS-171 to GRUAN Ozonesonde Programmes, performance monitoring is a non-real-time activity in which the performance of an individual GRUAN Ozonesonde Programme, or of an ensemble of GRUAN Ozonesonde Programmes, is examined for trends and systematic deficiencies. Performance monitoring within GRUAN Ozonesonde Programmes is primarily the responsibility of the Lead Centre and the TTR.

Certification and re-certification of GRUAN Ozonesonde Programmes is an essential component of performance monitoring. Examples of quantitative performance indicators are:

1. Ozonesonde SGDP downloads.
2. Number of candidate sites wishing to become a GRUAN Ozonesonde Programme.
3. Number of GRUAN sites participating in JOSIE and inter-comparison field campaigns, and conducting laboratory studies whose results appear in peer reviewed journals.
4. The number of peer reviewed publications in which GRUAN ozonesonde data products have been used.
5. The number of GRUAN Ozonesonde Programmes funded through national or international funding agencies.

All above indicators serve to provide a year-to-year traceability of GRUAN ozonesonde programmes' impact within the climate community.

ACRONYMS

ASOPOS: Assessment of Standard Operating Procedures for Ozone Sondes
BESOS: Balloon Experiment on Standards for Ozone Sondes
CRD: Converted Raw Data
DMT: Droplet Measurement Technologies
ECC: Electrochemical concentration cell
ECV: Essential Climate Variable
GATNDOR: GRUAN Analysis Team for Network Design and Operations Research
GAW: Global Atmosphere Watch
GCOS: Global Climate Observing System
GOASS: Ozonesonde Analysis Software System
GOME-2: Global Ozone Monitoring Experiment–2
GPS: Global Positioning System
GRUAN: GCOS reference upper-air network
IGACO: Integrated Global Atmospheric Chemistry Observations
IGPD: Integrated GRUAN Product Data
IMet: Intermet (radiosonde)
IOC: Intergovernmental Oceanographic Commission
JOSIE: Jülich Ozone Sonde Inter-comparison Experiment
LMS: Lockheed Martin Sippican
NDACC: Network for the Detection of Atmospheric Composition Change
NCAR: National Center for Atmospheric Research
NCEI: National Centers for Environmental Information
NMI: National Metrological Institute
NOAA: National Oceanic and Atmospheric Administration
OMI: Ozone Monitoring Instrument
PCF: Pump correction factors
CRD: Primary Raw Data
SAG: Science Advisory Group
SASBE: site atmospheric state best estimates
SGDP: Standard GRUAN Product Data
SHADOZ: Southern Hemisphere ADditional OZonesondes
SPARC: Stratosphere-troposphere Processes And their Role in Climate
SPC: Science Pump Corporation
Suomi-NPP: Suomi National Polar-orbiting Partnership
TEI: Thermo Environmental Instruments
TTR: Task Team on Sondes
UTLS: Upper Troposphere Lower Stratosphere
WCCOS: World Calibration Center for Ozone Sondes
WG-GRUAN: Working Group on GRUAN
WIGOS: WMO Integrated Global Observing Systems
WMO: World Meteorological Organization
WOUDC: World Ozone and Ultraviolet Data Centre

Appendix A.1: SHADOZ SOP CHECK LIST

Version: Mar 01, 2017 **SHADOZ DIGITAL OZONESONDE CHECKLIST**

INITIAL PREPARATION - NO LESS THAN 3 DAYS BEFORE FLIGHT.

OPERATOR INITIALS: ______
FLT # _______
DATE (YYYYMMDD): ___________________ Station:___________________________
O_3 SONDE SERIAL #: _______________
SOLUTION STRENGTH (1%, 0.5%, other)______________
1. Run 10 minutes on *no* O_3 air: ____ (√)
2. PUMP CURRENT: __________ (µA)
3. PUMP PRESSURE: __________ (psi)
4. PUMP VACUUM: __________ (in Hg)
5. Bypass Cathode chamber: Yes ___ No ___
6. Add 5-6cc Cathode solution: ____ (√)
7. Run 30 minutes on *HIGH* O_3: ____ (√)
8. Run 5 minutes on *no* O_3: ____ (√)
9. Dump Cathode solution: ____ (√)
10. ADD ___(√) 2.5CC or ___(√) 3.0 CC FRESH CATHODE (Wait 2 min): ____ (√)
11. ADD 1.5 CC ANODE SOLUTION: ____ (√)
12. Run 10 minutes on *no* O_3: ____ (√)
13. RECORD O_3 CURRENT: ________ µA
14. Run 10 minutes at 5µA O_3 ____ (√) - then switch to *no* O_3 air.
15. RECORD TIME TO DROP FROM 4.0 TO 1.5 µA: _________ sec.
16. Run 10 minutes on *no* O_3: ____ (√)
17. RECORD O_3 CURRENT: _______µA
18. Add additional ___(√) 2.5CC or ___(√) 3.0 CC of CATHODE : ____ (√)
19. Short the cell leads and store in Styrofoam box: ____ (√)

IF DORMANT AFTER 1 WEEK REPLACE SOLUTIONS.
DATE (YYYYMMDD) : __________________

1. CHANGE CATHODE SOLUTION: ____3cc or ___2.5cc (√)
2. CHANGE ANODE SOLUTION (1.5cc): ____ (√)
3. Run 5 minutes on *no* O_3 ____ (√)
4. RECORD O_3 CURRENT: _______ µA
5. Run 5 minutes on 5µA O_3 ____ (√)
6. Switch to *no* O_3: ____ (√)
7. RECORD TIME TO DROP FROM 4.0 TO 1.5 µA: _________ sec
8. Run 10 minutes on *no* O_3 – RECORD CURRENT: _________ uA
9. Short cell leads and Store in Styrofoam box: ____ (√)

DAY OF FLIGHT PREPARATION IN LAB.

OPERATOR INITIALS: _____
DATE (YYYYMMDD): ________________

1. Cathode solution # and date of bottle *(if applicable)*: ___________
2. CHANGE CATHODE SOLUTION: ____3cc or ___2.5cc (√)
3. CHANGE ANODE SOLUTION (1.5cc): ____ (√)
4. Run 10 minutes on *no* O_3: ____ (√)
5. RECORD O_3 CURRENT: BG#0 = _________ µA
6. Run 10 minutes at 5µA O_3: ____ (√)
7. Switch to *no* O_3: ____ (√)
8. RECORD TIME TO DROP FROM 4 TO 1.5 µA: _________ sec.
9. RUN 10 MINUTES ON *no* O_3 and RECORD O_3 CURRENT: BG#1 = ___________ µA
10. ROOM TEMP (C): _________, ROOM RH (%): __________, ROOM Pressure (hPa)__________
11. Flow rate Correction *(if calculated)*: ______________________%
12. RECORD T100 FLOWRATE TIMES:
    FLOWRATE #1: __________ sec
    FLOWRATE #2: __________ sec
    FLOWRATE #3: __________ sec
    FLOWRATE #4: __________ sec
    FLOWRATE #5: __________ sec
    AVERAGE T100:__________ sec

DAY OF FLIGHT AT THE LAUNCH SITE.

OPERATOR INITIALS: ______
RADIOSONDE TYPE/Model (Vaisala RS92, Modem M10, etc): ________________________
RADIOSONDE SERIAL #: ___________________
INTERFACE #:_______________________
O_3 BACKGROUND CURRENT BEFORE FLIGHT BG#2: __________ µA

GMT Date (YYYYMMDD): _________________
LOCAL date (YYYYMMDD): _________________
GMT Launch Time (HH:MM:SS): _______________
LOCAL Launch time (HH:MM:SS): ______________

BALLOON SIZE: ___________Grams: ____________
BALLOON TYPE: TOTEX ____ Hwoyee ____ PAWAN ____ (√ one)
NOAA FPH Serial # *(if applicable)*: ______________
Other instruments:____________________________________

SURFACE PRESS: ____________(hPa) SURFACE WIND SPEED: _________ (m/s)
SURFACE TEMP: _____________ (C) SURFACE WIND DIR: ____________ (deg)
SURFACE RH: ________________ (%)

Dobson *(if available)*: ________________(DU)
Brewer *(if available)*: ________________(DU)
Other *(if available)*: ______________(DU)

Sky Conditions and Remarks:

Appendix A.2: RECOVERED OZONESONDE CHECK LIST

Follows the NOAA/ESRL/GMD Check list

DATE (YYYYMMD): ______________
OPERATOR INITIALS: ________

Was this a ozonesonde recovered on day of flight? ____ Yes/No
If No, how many days between launch and recovery? ____days

HISTORY:
O_3 PUMP SERIAL #: ______________
FORMER FLIGHT #: ______________
DATE FLOWN (YYYYMMDD): ______________
DATE FOUND (YYYYMMDD): ______________
DATE RETURNED (YYYYMMDD): ______________

COMMENTS: OVERALL SONDE/PUMP CONDITION: (looks new, dirt or coloring around pump present, signs of corrosion anywhere, 0-ring condition, pump noisy?, etc.)

INITIAL RINSE/RECONDITIONING – SOON AFTER DELIVERY:

Check that the cam that drives the piston is not turning off-center, loose or rubbing too close to the metal frame. If it is too close or has come loose then the sonde will be noisy and run with a high current. Sonde should not be flown in this case.

Rinse off outside of cells with warm tap water. ____(√)
Squirt De-ionized water (DIW) through running pump inlet (2 or 3 times for about 5 seconds). ____(√)
Rinse cells and tubing with DIW. ____(√)
Fill cells about ¾ full of DIW. ____(√)
Store sheet and ozonesonde until ready for the 3-7 day pre-condition. ____(√)
Date stored on shelf until ready for the 3-7 day pre-condition (YYYYMMDD): _______________

During normal pre-conditioning preparations, an ozone calibrator, e.g. TEI, is strongly recommended to test the performance of the refurbished sonde. Re-conditioned sondes should not be flown if the sonde values are ±5% of calibrated source.

PRE-CONDITIONING CALIBRATION PROCEDURES:

DATE (YYYYMMDD): ________________________
Operator Initials: _______

Calibration Instrument/Model:_____________________________
Calibration Serial Number: _________________________

1. Run 50 ppbv O_3 for 10 minutes: ____ (√)
2. Record: CALIBRATOR: ______ ppbv OZONESONDE: _______ppbv % Difference: ____
3. Run 100 ppbv O_3 for 10 minutes: ____ (√)
4. Record: CALIBRATOR: ______ppbv OZONESONDE: _____ppbv % Difference: ____
5. Run 150 ppbv O_3 for 10 minutes: ____ (√)
6. Record: CALIBRATOR: ______ ppbv OZONESONDE: ______ ppbv % Difference: ____
7. Run 200 ppbv O_3 for 10 minutes: ____ (√)
8. Record: CALIBRATOR: ______ppbv OZONESONDE: ______ ppbv % Difference: ____
9. Run 50 ppbv O_3 for 10 minutes: ____ (√)
10. Record: CALIBRATOR: ______ppbv OZONESONDE: ______ppbv % Difference: ____
11. Run *no* ozone air for 10 minutes: ____ (√)
12. Record: CALIBRATOR: ______ ppbv OZONESONDE: ____ppbv % Difference: ____

If the percentage differences for the 100 ppbv and ozone-free air exceeds ±5% do not fly re-used sonde.

FINAL COMMENTS:

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