Citation: Kirchengast, G., Occultations for Probing Atmosphere and Climate: Setting the Scene, in Occultations for Probing Atmosphere and Climate (G. Kirchengast, U. Foelsche, A.K. Steiner, eds.), pp. 1-8, Springer, Berlin-Heidelberg, 2004.

Occultations for Probing Atmosphere and Climate: Setting the Scene

G. Kirchengast

Institute for Geophysics, Astrophysics, and Meteorology (IGAM),
University of Graz, Graz, Austria.

Abstract. Use of the occultation measurement principle for observing the Earth's atmosphere and climate has become so broad as to exploit solar, lunar, stellar, navigation and satellite-crosslink signals, to employ the electromagnetic spectrum from EUV/UV via VIS/IR and MW to Radio, and to utilize different kinds of atmosphere-radiation interaction such as refraction, absorption, and scattering. The geophysical parameters obtained – from the Earth's surface up through the complete atmosphere – extend from the fundamental mass field variables temperature, density, pressure, and geopotential height via the fundamental variable trace gases water vapor and ozone and many further trace species to particulate species such as aerosols and cloud liquid water. Furthermore, ionospheric electron density is sensed. Occultation methods all share the key properties of self-calibration, high accuracy and vertical resolution, global coverage, and (if using radio signals) all-weather capability. Occultation data thus bear enormous utility for applications in climate monitoring and research, weather analysis and numerical weather prediction, atmospheric physics and chemistry, and other fields such as space weather and planetary research. This paper introduces the general principles, capabilities, properties, and exploitation possibilities of occultation methods in order to furnish basic knowledge and insight on how they provide vital contributions to a better understanding of the Earth's atmosphere and climate system and to better prediction of its future evolution. By way of this general introduction the paper at the same time sets the scene for the wide range of important topics covered by this proceedings book of the 1st International Workshop on Occultations for Probing Atmosphere and Climate. References are selected such that most of them point to papers in the book.

1 Introduction

Since the early use of the occultation measurement principle for sounding planetary atmospheres and ionospheres, its exploitation in atmospheric remote sensing has seen tremendous advances. A particular boost was felt since the late eighties when a variety of intriguing opportunities for application to the atmosphere of our home planet Earth were increasingly recognized, such as utilizing new signal sources like Global Navigation Satellite Systems (GNSS).

Today we deal with and plan sensors on Low Earth Orbit (LEO) platforms, which exploit solar, lunar, stellar, GNSS, and LEO-crosslink signals. Also airborne and “mountain-top” platforms are explored. The sensors, together, smartly utilize the full range of the electromagnetic spectrum from UV to radio waves and exploit different types of atmosphere-radiation interaction such as absorption and scattering, both by molecules and aerosols, as well as refraction. The atmospheric variables collectively obtained, over the entire globe and from the atmospheric boundary layer up to LEO platform heights, comprise the fundamental variables temperature, density, pressure, geopotential height, humidity, and ozone as well as many other gaseous and particulate species such as key trace species of ozone chemistry, aerosol concentrations, and ionospheric electron density.

All occultation methods rest on one and the same occultation measurement principle with its properties of providing self-calibration, high accuracy and vertical resolution, global coverage, and, in case of radio signals, all-weather capability. Occultation data are thus of great value in a wide diversity of scientific fields including climate monitoring and research, numerical weather prediction and analysis, atmospheric physics and chemistry, ionospheric research and space weather, and planetary science. The self-calibration property is particularly crucial for climate change monitoring, as it enables unique long-term stability in climate datasets. The latter can be built from occultation data of different satellites and times without inter-calibration efforts. In fact, a controversy such as the recent one on the tropospheric temperature record over the last two decades, involving the heavily calibration-dependent Microwave Sounding Unit (MSU) data, could have been presumably saved had suitable occultation data been available.

Along the above lines, this paper provides a general introduction to the measurement concept, methods, and characteristics as well as to the data processing, properties, and exploitation possibilities of occultation systems for probing Earth's atmosphere and climate. It is organized as follows. In Section 2, the measurement concept and methods are introduced, followed by overviews on measurement characteristics in Section 3 and occultation data processing in Section 4. The unique properties of occultations, being the basis for their broad scientific exploitation potential, are summarized in Section 5. Main areas of use are then addressed in Section 6, where the utility of occultation data for climate monitoring is highlighted as an exploitation example of particular promise. Finally, concluding remarks are provided in Section 7.

2 Occultation Measurement Concept and Methods

The generic concept of any spaceborne atmospheric occultation measurement system is illustrated in Figure 1. The three main components are 1) a source transmitting electromagnetic (EM) signals, 2) propagation of the EM signals through the atmosphere in limb sounding geometry, whereby they get modified by interaction with the atmospheric medium (=occulted), and 3) a sensor recording properties of the occulted EM signals, which carry the desired information on the atmospheric state of the region which was passed during propagation.

In real systems, these three generic components can receive a wide diversity of realizations summarized below.

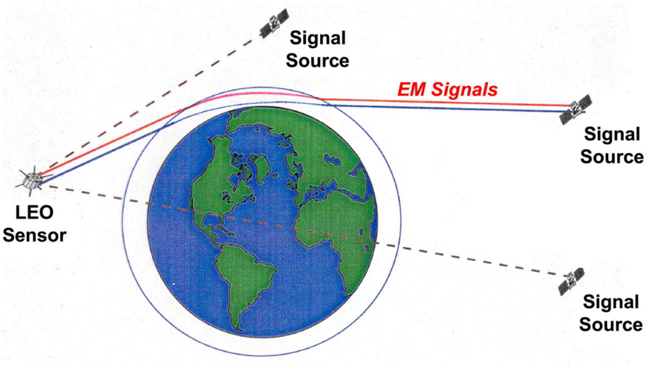

Fig. 1. Schematic illustration of the occultation measurement concept (generalized from a figure of D. Feng, IAP/Univ. of Arizona, Tucson).

1) *Signal source.* Main natural sources used are sun, moon, and sufficiently bright stars, which transmit broadband thermal EM radiation (Planck radiation) in the UV/VIS/IR range exploitable by spectro-radiometric occultation sensors. Artificial sources used are transmitters on satellites (as shown in Fig. 1 as example sources), most notably on navigation satellites of the GNSS (comprising the U.S. GPS system, the Russian GLONASS system, and in future the European Galileo system). GNSS satellites transmit specifically designed highly stable radio signals in L band (1–2 GHz range) exploitable by GNSS radio-frequency receivers as sensors. Additionally, LEO platforms are planned to carry transmitters in the future, carefully designed as part of novel LEO-crosslink systems using MW/Radio signals. Signal source intensities are in all cases selected to be of sufficient strength to ensure a high signal-to-noise ratio (SNR) at the sensor (order 20–40 dB) for unattenuated signals "above the atmosphere", in order to provide adequate measurement precision also for the occulted signals which passed the atmosphere.

2) *Propagation of EM signals.* Having selected a set of wavelength channels within the EM spectrum, with the detailed signal properties chosen by signal source and sensor definition, the propagation through the atmosphere will, basically, lead to a mixture of absorption, scattering, refraction, dispersion, and polarization effects collectively occulting the signal. However, real systems usually have their channel set and signal properties defined in a way so that most of these radiation-medium interaction effects are negligible or intrinsically correctable for the signals of interest and that only absorption by species of interest and/or refraction governed by the atmospheric refractivity field play major roles. The two main measurement modes are thus absorptive occultation, where mainly the absorber-induced intensity damping is utilized (Beer-Lambert's law), and refractive occultation, where it is mainly the bending of propagation paths (Snell's law and Fermat's principle). In the relatively dense troposphere, generally absorption and refraction together play a role, and multipath propagation, diffraction, and super-refraction (in the lowest kilometers) can occur in regions of sharp refractive structures (e.g., Sokolovskiy 2004), requiring more complex system designs for tropospheric sounding. Furthermore, in some spectral-spatial domains, signal scintilla-

tions induced by random small-scale refractivity irregularities due to atmospheric turbulence may degrade the SNR of signals carrying the desired information on the atmospheric state (e.g., Kyrölä et al. 2004; Cornman et al. 2004).

3) *Sensor.* Sensor platforms for spaceborne occultations are commonly LEO satellites (as illustrated in Fig. 1). Also airborne and "mountain top" platforms have been suggested (Lesne et al. 2002; Zuffada et al. 1999). Compared to LEO platforms, the latter lead to important differences in concept and data processing (not further addressed in this paper). In case of optical wavelengths (UV/VIS/IR), sensors are usually spectro-radiometers pointed towards the signal source(s) and measuring occulted signal intensities with adequate temporal resolution and precision for all channels of interest. Given a sufficiently precise sensor pointing (order 1–10 μrad), also the refractive bending of the propagation paths ("angle of arrival") can be directly measured. In case of radio and MW wavelengths, sensors are usually heterodyne radio-frequency receivers, which, utilizing occulted navigation signals from highly stable sources such as the GPS, can measure signal amplitude and phase (complex signal) with high sampling rate and precision.

The main atmospheric occultation methods used in practice, or prepared currently, are GNSS–LEO radio occultation (chapter 2 of this book), LEO–LEO radio occultation (chapter 3 of this book), and stellar and solar optical occultation (chapter 4 of this book). The papers in these chapters, and the references therein, provide a fair starting point for detailed information on each of the methods.

3 Occultation Measurement Characteristics

The properties of occultation observing systems are driven by specific measurement characteristics such as the way of profile acquisition, the self-calibration principle, the available accuracy and resolution, and the geographic sampling. Here a generic overview on these characteristics is given.

Occultation profile acquisition. In order to enable the signal propagation paths to scan a desired vertical depth of the atmosphere (order 10 to 100 km) within a time over which the measured atmospheric state is reasonably static (< 10 min), sensor and/or signal source are required to move in a way to ensure a sufficient vertical scan velocity (order 100 m/s or faster). Acquisition of one full measurement profile through the depth of the atmosphere constitutes one occultation event, taking the order of 1 min in real spaceborne systems which feature vertical scan velocities of order 1 km/s mainly thanks to the orbital motion of the LEO sensor. Such an event, termed "setting" if the scan progressed downward towards Earth's surface, otherwise "rising" if it progressed upward towards space, forms the basis for any subsequent data processing towards atmospheric profiles.

Self-calibration. The important self-calibration property of occultation events denotes the fact that amplitude or intensity and phase path measurements are normalized to the unattenuated, straight-line "above the atmosphere" measurements acquired at the start of a setting and the end of a rising event, respectively. Atmospheric profiles are thus not derived from absolute intensities or phase delays but only from transmission (normalized intensity) and Doppler shift (phase change) profiles requiring no external calibration and only short-term measurement stability over the order of 1 min of event duration. With each single event intrinsically calibrated this way, and using proper "frozen-in" data processing, the long-term stability of any derived multi-year climate dataset is automatically ensured.

Accuracy and resolution. As the signal sources are generally point-like sources and enable high SNR, high vertical resolution (about 1 km or better) and accuracy (order 1% or smaller relative errors) of derived profiles can be achieved. This requires a sufficient data sampling rate (at least 2 samples/sec or more) and instrumental precision (order 0.1% for main observables) over each event, which real occultation sensors do furnish. The horizontal resolution is about 300 km, arising from the near-exponential density decrease with height of the bulk air and of most atmospheric species, i.e., the essential part of atmospheric information is accrued within about ±150 km of the tangent point, the point of closest approach to the Earth's surface of a propagation path. Derived atmospheric profiles thus represent the atmospheric state at and around the tangent point trajectory traced out by the occultation event (Foelsche and Kirchengast 2004; Syndergaard et al. 2004).

Geographical coverage. The number and geographic distribution of occultation events measured within a given time period, e.g., per day, primarily depends on the number and (moving) positions of the signal sources and sensors involved in an occultation observing system. It can vary by orders of magnitude amongst different systems. For example, a solar occultation sensor aboard a single LEO satellite exploiting the sun as its single signal source can collect only near 30 events per day at sunrise/set latitudes (one rising and one setting event per orbital revolution of the LEO platform), whilst a small constellation of six GNSS occultation sensors in LEO exploiting the GPS system of nominally 24 GNSS signal sources can collect over 3000 events per day with full global coverage.

4 Occultation Data Processing

The data processing of occultation data towards atmospheric profiles, given Doppler shift and/or transmission profiles from pre-processing of raw observables, proceeds generically as follows.

Bending angle and optical thickness/columnar content retrieval. Doppler shift profiles are converted to atmospheric bending angle profiles, using precise positions and velocities of signal source and sensor, and transmission profiles to optical thickness or limb columnar content profiles, using Beer-Lambert's transmission law and corrections for signal defocusing and spreading as required. In complicated (lower) troposphere situations involving multipath propagation and diffraction of (radio) signals, more elaborated wave-optical methods may be used for this processing step (e.g., Gorbunov 2004).

Refractivity and absorption coefficient/number density retrieval. Bending angle profiles are converted, via a classical Abel transform, to refractivity profiles, and optical thickness or columnar content profiles, via another Abel transform, to absorption coefficient (or, equivalently, imaginary refractivity) or number density profiles of absorbing species of interest.

Atmospheric profiles retrieval. Refractivity and absorption coefficient profiles can be further processed, using basic laws such as refractivity equation, hydrostatic equation, equation of state, and absorption coefficient formulations (spectroscopic models), to atmospheric profiles of temperature, density, pressure, geopotential height, and densities of absorber species, like of water vapor, ozone or any other species to which a given occultation system is sensitive.

For details on the data processing as applied to different specific occultation methods, useful entry points in this book are chapter 1 and, for example, Larsen et al. (2004), Kursinski et al. (2004), Yee et al. (2004), and Bernath (2004).

Alternatively, the above step-by-step retrieval processing can be substituted by a data assimilation approach (e.g., 1D-variational assimilation, 1DVAR), where "observed" profiles after a certain processing step (e.g., refractivity and absorption coefficient profiles) are forward modeled from a priori profiles of the desired atmospheric variables, which are then updated to "analyzed" profiles optimally consistent with the "observed" profiles (e.g., Healy and Eyre 2000). On a larger scale, more complex systems, such as numerical weather prediction systems using 3DVAR or 4DVAR, can assimilate complete global datasets from occultation observing systems, together with data from other observing systems, and achieve in this way consistent global analysis fields of many essential variables of the atmospheric state (e.g., Bouttier and Courtier 1999).

5 Unique Properties for Atmosphere and Climate Science

Occultation systems can provide vital contributions to many fields of atmosphere and climate science (see Section 6) due to the following set of unique properties:

- *long-term stability* due to the intrinsic self-calibration of occultation data
  - self-calibrated Doppler shift profile measurements (time standard)
  - self-calibrated transmission profile measurements (normalized intensity)
  (detecting, e.g., < 0.1K/decade temperature and < 2%/decade humidity drifts)
- *high accuracy and vertical resolution* resolving atmospheric fine structures
  (achieving, e.g., < 1 K temperature and < 10% humidity error at 1 km height resolution in individual profiles)
- *global and even coverage*, equal over both oceans and land
  (providing, e.g., the same data quality above Antarctica as above Europe)
- *all-weather capability*, i.e., accurate data on gaseous air variables like temperature, humidity, and trace gases also in presence of clouds and aerosol
  (if wavelengths > 1 cm, e.g., in GNSS-LEO and LEO-LEO radio occultation)
- *utility as climate reference datasets*, i.e., data from an occultation mission need no inter-calibration (and no overlap) with other occultation missions
  (allowing, e.g., use as benchmark data for climate monitoring and for validation and improvement of atmosphere and climate models)

- *dense array of profiles* when using constellations of satellites
  (enabling, e.g., regional climate monitoring and significant improvements of atmospheric forecasting such as of medium-range weather prediction)

While the detailed realization of these properties will vary from one specific occultation system to another (e.g., between a GNSS-LEO and a solar occultation mission), they are shared in their general sense by all occultation systems.

6 Areas of Use in Atmosphere and Climate Science

Occultation data are of high value in a variety of fields and used for a multitude of different research and application purposes in these fields. Only a very brief and high-level summary of areas of use is thus possible here as follows:

- *climate monitoring and research*
  (monitoring of climate variability and change, global climatology algorithms and products on key climate variables, climate model validation and improvement, anthropogenic climate change detection and attribution, climate process studies, e.g., on climate feedbacks, external climate forcings)
- *atmospheric physics and chemistry*
  (a wide range of atmospheric process studies, e.g., on gravity waves, troposphere/stratosphere exchange, tropics/extratropics heat and mass exchange, ozone chemistry, cloud and aerosol physics, atmospheric turbulence)
- *operational meteorology*
  (numerical weather prediction, atmospheric analyses, improving models)
- *ionosphere, space weather, and planetary research*
  (ionosphere, space, and planetary climate, weather, and process studies)

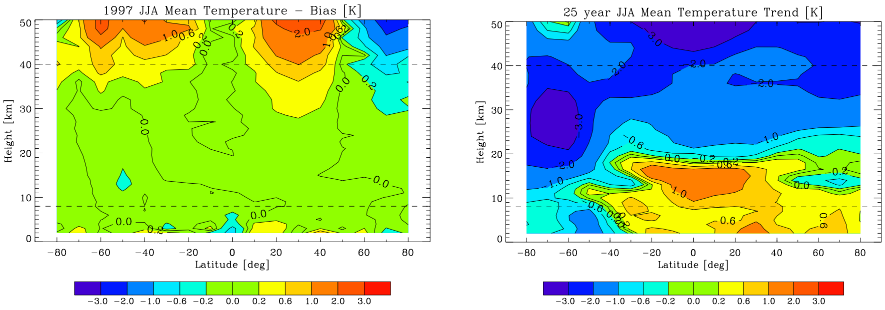

Fig. 2. Residual bias errors in a summer climatology of temperature derived from GNSS-LEO occultation data (left) compared to summer temperature trends 2001–2025 derived from a climate model prediction (right) (from Kirchengast and Hoeg 2004; preparation of figure by A. Gobiet and U. Foelsche, IGAM/Univ. of Graz, Austria; for more information regarding the left panel see also Gobiet and Kirchengast 2004).

As one example of use, Figure 2 illustrates the high utility of GNSS-LEO occultation data for climate monitoring. It indicates that climate trends expected over the coming decades will be reliably detectable by the data thanks to their long-term stability and accuracy. For more details regarding areas of use, good starting points in this book are Kirchengast and Hoeg (2004), from which Fig. 2 was taken, Kursinski et al. (2004), Yee et al. (2004), Bernath (2004), and chapter 5.

7 Conclusions

An introduction was given to the measurement concept, methods, and characteristics as well as to the data processing, unique properties, and areas of use of occultations for probing atmosphere and climate. Occultation observing systems evidently can provide essential contributions to a better understanding of the Earth's atmosphere and climate system and to better weather and climate prediction.

Furthermore, by way of this general introduction, the scene was set for the broad range of topics covered by the five chapters of this book. It is the first book covering occultation science over the full range from methodology in general (chapter 1) via specific methods (GNSS-LEO, chapter 2; LEO-LEO, chapter 3; stellar and solar, chapter 4) to the use of occultation data (chapter 5).

References

Bernath P (2004) OPAC-1 Springer Proc Book, this issue, 319–331

Bouttier F, Courtier P (1999) Data assimilation concepts and methods. Met Training Course Lecture Notes (www.ecmwf.int/newsevents/training), ECMWF Reading, U.K., 58 pp

Cornman L, et al. (2004) OPAC-1 Springer Proc Book, this issue, 365–373

Foelsche U, Kirchengast G (2004) OPAC-1 Springer Proc Book, this issue, 127–136

Gobiet A, Kirchengast G (2004) OPAC-1 Springer Proc Book, this issue, 137–148

Gorbunov ME (2004) OPAC-1 Springer Proc Book, this issue, 11–24

Healy SB, Eyre JR (2000) Retrieving temperature, water vapour and surface pressure information from refractive index profiles derived by radio occultation: A simulation study, Q J R Meteorol Soc 126: 1661–1683

Kirchengast G, Hoeg P (2004) OPAC-1 Springer Proc Book, this issue, 201–220

Kursinski ER, et al. (2004) OPAC-1 Springer Proc Book, this issue, 173–187

Kyrölä E, et al. (2004) OPAC-1 Springer Proc Book, this issue, 275–287

Larsen GB, et al. (2004) OPAC-1 Springer Proc Book, this issue, 111–118

Lesne O, Haase J, Kirchengast G, Ramsauer J, Poetzi W (2002) Sensitivity analysis for airborne sounding of the troposphere by GNSS radio occ. Phys Chem Earth 27: 291–299

Sokolovskiy S (2004) OPAC-1 Springer Proc Book, this issue, 39–51

Syndergaard S, et al. (2004) OPAC-1 Springer Proc Book, this issue, 221–232

Yee J-H, et al. (2004) OPAC-1 Springer Proc Book, this issue, 261–273

Zuffada C, Hajj GA, Kursinski ER (1999) A novel approach to atmospheric profiling with a mountain-based or airborne GPS receiver. J Geophys Res 104: 24435–24447