R. LEITINGER and H. O. RUCKER

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von Herrn

em.o.Univ.-Prof. Dr. Siegfried J. Bauer

Institut für Geophysik, Astrophysik und Meteorologie
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FOREWORD

On behalf of the Institute for Geophysics, Astrophysics, and Meteorology of the Karl–Franzens University of Graz and the Department of Extraterrestrial Physics of the Space Research Institute of the Austrian Academy of Sciences the editors R. Leitinger and H. O. Rucker dedicate this publication on the occasion of his 70th anniversary to

em.o.Univ.–Prof. Dr. Siegfried J. Bauer.

The collected articles give a review of the scientific work successfully performed at the two Institutes during the last two decades of Prof. Bauer's directorship and provide an outlook to future perspectives.

The authors especially would like to thank the jubilee for the nice and hearty atmosphere which distinguished the Institutes during all these years and for the support of the scientific development and independence.

Graz, October 2000

R. Leitinger H. O. Rucker

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ATMOSPHERIC PHYSICS, ATMOSPHERIC REMOTE SENSING, AND CLIMATE SYSTEM RESEARCH: A REVIEW ON 10 YEARS GONE AND AN OUTLOOK

G. Kirchengast*

Abstract

This article provides a personal review of my research performed in the realm of the Earth's atmosphere within the last ~10 years (from the completion of my M.Sc. thesis up to present) and closes with an outlook on future activities. The fields of research addressed are reasonably circumscribed by the title and I will browse through them in form of a survey on activities and results, which I find most relevant. All atmospheric regions, upper atmosphere (thermosphere and ionosphere), middle atmosphere (stratosphere and mesosphere), and troposphere, respectively, have been addressed over the years; with focus in the first half of the time on upper atmosphere research and focus since 1996 on atmospheric remote sensing and climate system research. The closing outlook on future activities planned (or envisioned) in the latter field shall indicate (or raise hope, at least) that intriguing science is in the pipe also for the years to come.

I believe the scope of the article to be very fitting for this "Festschrift" for Prof. Siegfried J. Bauer, who so actively supported my scientific life throughout all the years. He acted as a truely professional mentor, with an admirable ability to offer just the right combination of a very high degree of freedom and a very rich source of senior advice if required. I thus dedicate this article with pleasure, and with deep respect and gratitude, to Siegfried Bauer on the occasion of the 70th return of his birthday. Furthermore, I find it appropriate to take this opportunity to express equal respect and gratitude to my other primary scientific mentor, Prof. Reinhart Leitinger, who as well provided distinguished support and co-operativeness all the time from his supervision of my M.Sc. and Ph.D. work onwards. I thus co-dedicate this article to Reinhart Leitinger, who celebrated the 60th return of his birthday this year.

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1 Introduction

"Atmospheric physics" is understood in this article in the broad sense of comprising all physics, be it related to the neutral or the ionized gas or both, which takes place in the domain within the Earth's surface and a height of roughly about 1000 km. The latter height, the "top of the atmosphere", strongly depends on context and may be adopted everywhere from about 500 km (thinking of the exobase, where the mean free path of neutral gas particles starts to exceed the local scale height) up to about 1500 km (thinking of a height, where the number of light hydrogen ions in the ionized gas certainly exceeds the one of heavier ions, most notably atomic oxygen ions). If one adopts a distinctly narrow view in some meteorological contexts, the "top" may even lie as low as 10–15 km (near the tropopause). I like to ignore such narrow definitions, however, since I clearly prefer a broad view on atmospheres, in line with Siegfried Bauer, who fostered such a view with many distinguished scientific contributions; see, for example, the books Bauer (1973), and Bergmann–Schaefer/Band 7 (1997). Further recommendable books are Salby (1996), on lower atmosphere, and Rees (1989), on upper atmosphere, together providing a good general introduction to atmospheric physics. All papers of the survey below can be considered to fall into this broad and exciting field: Each has contributed directly or indirectly to the advancement of our understanding of the physics of the atmosphere in the sense defined.

"Atmospheric remote sensing" is understood to comprise all indirect measurement techniques, and the corresponding data analysis methodologies used to extract geophysical information, which provide us with observations of physical variables in the atmospheric domain defined above. Recommendable introductory books to this field, characterized (unfortunately) by a very heterogeneous bookstock, include (but are not limited to) Elachi (1987) (general), Janssen (1993) (microwave), Hanel et al. (1992) (infrared), Slater (1980) (optical/visible), Huffman (1992) (ultraviolet), Kohl et al. (1996) (radio/ionospheric remote sensing), Kingsley and Qeagan (1992) (RADAR), Measures (1984) (LIDAR), and Rodgers (2000) (data analysis/inverse theory and methods). Many papers of the survey, in particular those from more recent years, have contributed to advance different atmospheric remote sensing techniques and data analysis methodologies. The underlying objective of these activities is to globally improve the observational database of fundamental atmospheric variables (such as temperature, water vapor, and ozone); a research playing a key role for enabling advancements in a range of areas within atmospheric physics and climate system research.

The "Climate system" is understood to comprise everything from the bottom of the Earth's crust (lithosphere) up to the "top of the atmosphere", which is non-static at time scales from months to millions (or even billions) of years. Within this enormously complex system we focus interest on changes in the atmosphere, the most dynamic subsystem of the whole climate system, from seasonal to decadal scales. This is still a very broad area, within which both natural climate processes and (increasing) human influences on climate play prominent roles. Recommendable introductory books include (among others) Peixoto and Oort (1992), Graedel and Crutzen (1993; 1994), IPCC (1996), von Storch and Flöser (1999), and Lozán et al. (1998; 2001). Furthermore, a recommendable booklet, giving a concise (< 20 pages) introductory summary on the topic of "climate change", was recently provided by Hupfer et al. (2000a; 2000b). The most recent work of my survey, and work planned for the (immediate) future, addresses questions of natural and anthropogenic climate variability over the last few and next few decades, with particular focus on detection of climatic changes in the lower and middle atmosphere.

The article is organized as follows. Section 2 mainly introduces to early work around 1990 and surveys results of my M.Sc. and Ph.D. work. Section 3 mainly addresses work of my post-doc and "habilitation preparation" phase until 1996. Work from the first ∼2.5 years after I founded, at the beginning of 1996, a research group on atmospheric remote sensing is discussed in Section 4. In Section 5, selected papers of the most recent phase (about the last 2 years) are introduced, which report on research mostly performed within the framework of the Atmospheric Remote Sensing and Climate System (ARSCliSys) Research Group, as I named my group at the beginning of 1999 after we had achieved some consolidation. Section 6 concludes the article with a brief outlook on planned and envisioned future activities within my group and the Institute.

A warning is in order, finally, on my use of convenient but simplifying terms such as "my research" and "my work": The "my" is not to be taken too strictly. As the authors lists of the papers indicate, a majority of the research could only be realized in team efforts together with quite a number of creative, bright, and dedicated fellow scientists, more senior ones in the early years and mainly Ph.D. students and young Post-docs in more recent years (see Acknowledgments and References at the end of the article).

2 Time Series Analysis and Ionospheric Modeling

2.1 Time Series Analysis and Application to Ionospheric Data

"Simultaneous analysis of three geophysical time series — a software tool based on triple correlation theory and its application to traveling ionospheric disturbances (TIDs) for obtaining gravity wave parameters" is roughly the English translation of the somewhat lengthy title of my M.Sc. thesis (Kirchengast, 1988). The essential parts were presented at the 1989 European Geophysical Society meeting in Barcelona (my first talk at international level) based on the following abstract by Kirchengast and Leitinger (1989):

> TID investigation by means of triple correlation. — A new tool was developed useful for TID investigation: triple correlation combining data from three stations. The main properties of the method are presented together with results gained from the stations Graz, Lindau/Harz, and Firenze.

Figure 1 illustrates the results of the triple correlation analysis for an exemplary case of three Total Electron Content (TEC) time series. The desired result are the two relative time delays amongst the three wavelike Delta-TEC time series (panel b), which maximize the triple correlation (joint correlation of all three series). Panel c shows the triple correlation matrix (rows: delay of series 2 vs. series 1, columns: delay of series 3 vs. series 1), which quantifies the desired delays with its maxima. These correlation maxima are (quasi-)periodic with the (quasi-)period of the wavelike structures. The delay estimates

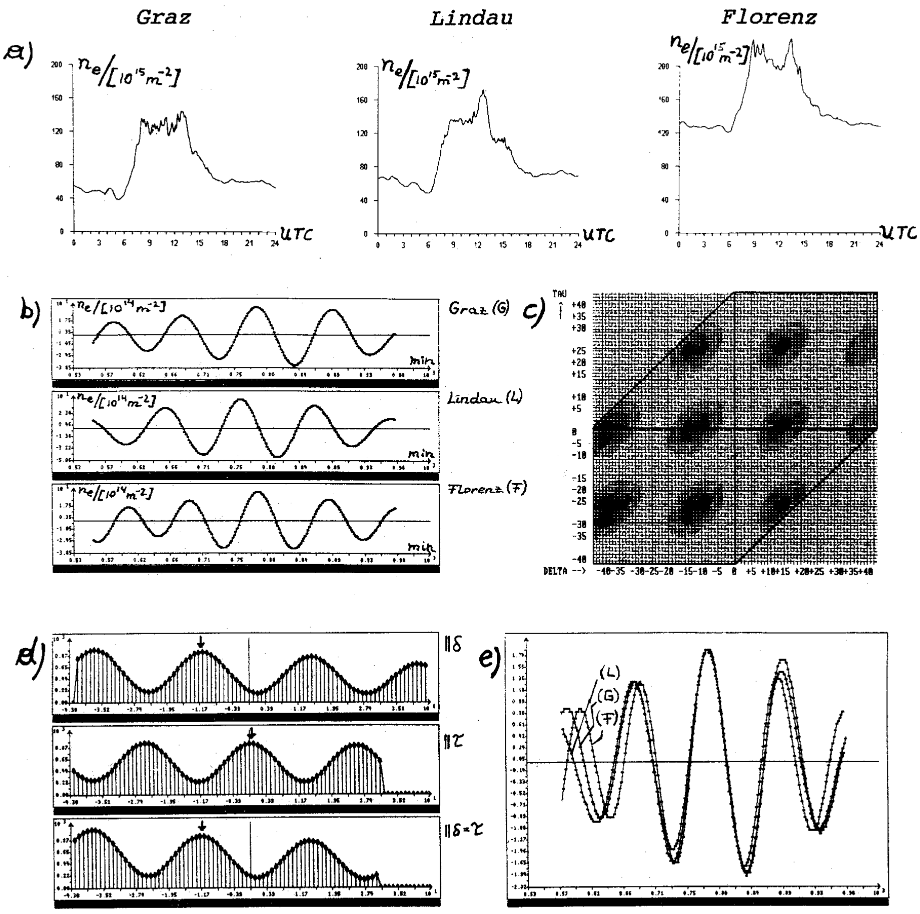

Figure 1: Illustration of the different ingredients involved in a triple correlation analysis of three time series. The specific case shown is concerned with the detection of relative time delays amongst three Delta-TEC time series. From Kirchengast (1988).

have in turn been used in the work, together with the period estimate, for reconstructing the direction and speed of horizontal propagation as well as the horizontal wavelength of an atmospheric gravity wave presumed to induce the Delta-TEC signatures (traveling ionospheric disturbances).

The lasting result of this work was the development of an efficient numerical time-domain algorithm for computing the triple correlation matrix based on an arbitrary set of three time series. Furthermore, determination of wave propagation parameters from wavetrains simultaneously measured by a suitably spaced triangle of sensors, as successfully demonstrated by the work, is certainly a particularly important geophysical application, since waves are a phenomenon of interest in many geophysical domains including atmosphere, oceans, and the solid Earth. Unfortunately I never found time to publish the essentials of the work in a journal (though I have no doubt as to its acceptability to that end).

2.2 Theoretical Modeling of the Ionospheric F Region

In my Ph.D. work, reported in Kirchengast (1992), I developed a quasi-realistic theoretical ionospheric model of the ionospheric F region at non-equatorial latitudes and performed, as an initial application, exemplary simulations of TID signatures from different potential causative mechanisms. I significantly extended and enhanced the theoretical model, named Graz Ionospheric Flux Tube Simulation (GIFTS) model, in course of my post-doc work until 1995 and described the final model in detail in Kirchengast (1996b) and, in a more concise form, in the book chapter Kirchengast (1996a). The Introduction of Kirchengast (1996a) provides a good overview on the GIFTS model (modified in references):

> The Graz Ionospheric Flux Tube Simulation (GIFTS) model is a mathematical model of the ionospheric F–region at mid– and high–latitudes. It is based on a set of hydrodynamic transport equations which is a suitably adapted form of the so–called 13–moment approximation (e.g., Schunk, 1977). The model can be applied along magnetic field lines at arbitrary non–equatorial sites encompassing the height range between 150 km and 600 km. It yields the field–aligned time–dependent evolution of the electron density, n_e, the field–aligned ion velocity, v_i, and the ion and electron temperatures, T_i and T_e, respectively, in a self–consistent way. The number densities of the major ion species $(O^+, NO^+, O_2^+, N_2^+)$ are simultaneously deduced, assuming photochemical equilibrium with respect to the molecular species. Optionally, a coupled system of meridional and zonal neutral wind equations is self–consistently included. This, in addition, yields the evolution of the meridional, u_n, and zonal, v_n, wind velocities in the thermosphere.
>
> The GIFTS model takes account of the relevant physical processes of the mid– and high–latitude F–region, including production of the plasma and of heat due to EUV irradiance and electron precipitation, chemistry of metastable and stable ions, neutral winds (forced by horizontal pressure gradients, Coriolis deflection, viscosity, and ion drag when self–consistently treated), field–aligned diffusion, thermal and frictional heat transfer between ions, electrons and neutrals, electron heat conduction and heating due to field–aligned currents, and plasma advection due to $\mathbf{E} \times \mathbf{B}$ drift. Model runs can be performed with high spatial and temporal resolution (e.g., 1 km and 1 min) in reasonable computing times and experience shows that realistic results can be obtained for a wide range of geophysical conditions.
>
> Originally, the GIFTS model was developed as a plasma density and transport model yielding n_e and v_i as described by Kirchengast et al. (1992a), i.e., ion and electron temperatures were required as input. As a next step an ion energy equation was included; a detailed description of the model at this stage is given by Kirchengast (1992). Recently, an appropriate electron energy equation was added which enabled the model to handle the whole set of fundamental ionospheric parameters (n_e, v_i, T_i, T_e) self–consistently. One–to–one comparisons of model results with incoherent scatter data described by Kirchengast et al. (1995a) indicate the reliability and usefulness of the model at this stage. Neutral wind equations also were recently included as an option which allows better account for ionosphere–thermosphere momentum coupling in some high–latitude studies. A report giving a complete up–to–date description of the GIFTS model is available upon request from the author (Kirchengast, 1996b). Details not given in the more concise description in this chapter are found there.

Figure 2 illustrates exemplary climatological results of simulations performed at the European Incoherent Scatter (EISCAT) radar site near Tromsø, Norway. GIFTS results on

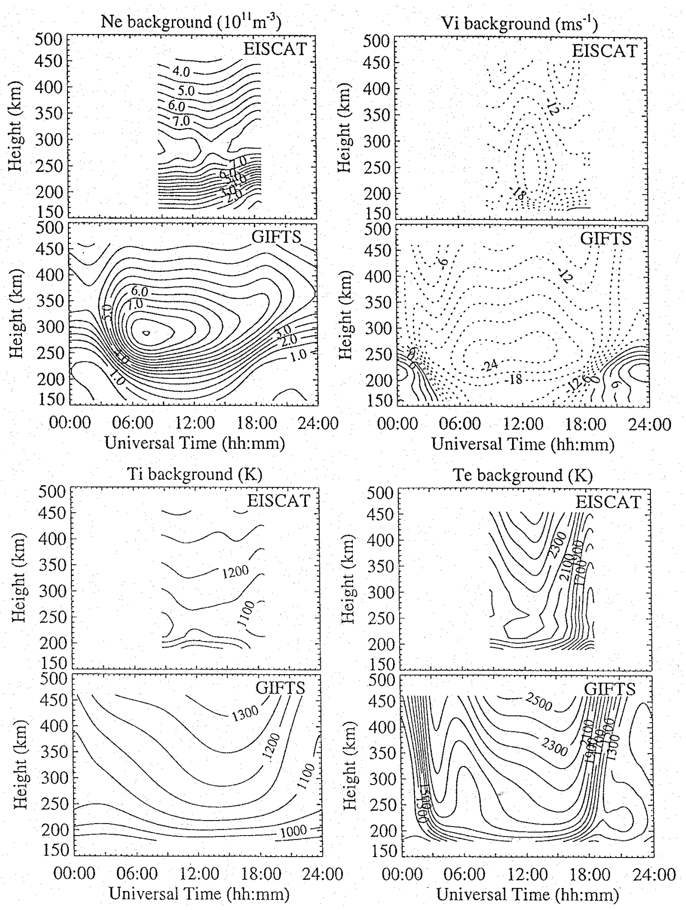

Figure 2: One–to–one comparison of climatological GIFTS model results to EISCAT data (lowpass-filtered to exclude periods <3 hrs) for a near–equinox day during moderate solar activity (Sep 6, 1988; F10.7 index: 152). From Kirchengast (1996b).

n_e, v_i, T_i, and T_e are compared with EISCAT data in a one-to-one manner. As the Figure indicates, the GIFTS model has the capability to fairly well predict the climatological behavior of the ionosphere in all fundamental parameters computed.

The GIFTS model has been applied with great success in a series of studies in the field of ionosphere-thermosphere weather modeling (Kirchengast et al., 1992b; 1993; 1994; 1995a; 1995b; 1996; Kirchengast, 1996c; Kirchengast, 1997), selected results of which are introduced in Section 3. Furthermore, it has been found of value for time-dependent, three-dimensional modeling of the mid-latitude ionosphere (Skedel et al., 1993; Leitinger et al., 1994). A confirmation of the scientific quality of the GIFTS model was the invitation by Robert W. Schunk (Center for Atmos. and Space Sciences, Utah State Univ., U.S.A.) to contribute a chapter (Kirchengast, 1996a) to the “STEP Handbook on Ionospheric Models”, which is utilized still today as a top reference to the leading ionospheric models worldwide. Though I myself did no longer employ the model post 1996 (except for ensuring successful transfer from DEC/VMS FORTRAN-77 to Unix GNU FORTRAN-77 in 1998 given that the VMS operating system was to become obsolete), it is still of good use in other centers (e.g., the MPI für Aeronomie in Lindau/Harz, Germany, and the Wuhan University in Beijing, China).

3 Ionosphere–Thermosphere Weather Modeling and Ionospheric Tomography

3.1 Ionosphere–Thermosphere Weather Modeling

The essential parts of my contributions to this field have been collected in my "Habilitationsschrift" (Kirchengast, 1996d) entitled "Traveling ionospheric disturbances caused by atmospheric gravity waves: from qualitative to quantitative insight", which was mainly based on the work described in Kirchengast et al., 1995a; 1996; Kirchengast, 1996c; 1997; and Hocke et al., 1996. Further work related to this topic includes Kirchengast et al., 1992b; 1993; 1994; 1995b. An informative summary of the key results was provided by the conclusions ("Schlußfolgerungen") of the six-page overview of Kirchengast (1996d) (in German; for an English summary best see the Abstracts and Summary and Conclusions sections of the 5 papers referred to as the main basis above; TID, traveling ionospheric disturbance; AGW, atmospheric gravity wave):

> (i) Das physikalische Verständnis des AGW–TID Zusammenhanges konnte mit Hilfe validierter, realistischer Modellierung und systematischer analytischer Behandlung der relevanten Prozesse der Thermosphären–Ionosphären Wechselwirkung von einem lückenhaften und in vielen Punkten qualitativen Verständnis zu einem soliden quantitativen bezüglich aller AGW/TID–Grundgrößen erweitert werden. Insbesondere die Klärung der Physik der TID in der Elektronentemperatur betraf einen bisher quantitativ völlig offenen Punkt. Die erarbeiteten analytischen Beziehungen sind auch über den AGW–TID Zusammenhang hinaus zum Verständnis anderer Phänomene der Thermosphären–Ionosphären Wechselwirkung nützlich. Weiters wurde das Verständnis der typischen Variabilität von AGW/TIDs in Abhängigkeit von unterschiedlichen AGW–Wellenparametern und thermosphärisch–ionosphärischen Hintergrundbedingungen vertieft.
>
> (ii) Die als Basismethode benützte realistischen Modellierung des AGW–TID Zusammenhangs wurde anhand von 1:1 Vergleichen zwischen Simulationsresultaten und Incoherent–Scatter (IS) Daten der EISCAT Radaranlage für verschieden Jahreszeiten und Sonnenaktivitäten erfolgreich validiert. Die wesentlichen Modellwerkzeuge, das eigenentwickelte GIFTS Modell und das eigenverbesserte realistische AGW Modell, erwiesen sich also als sehr gut geeignet zur Behandlung der komplexen Neutralgas–Plasma Wechselwirkung in der Hochatmosphäre. Das GIFTS Modell ist nach Wissen des Autors derzeit auch weltweit das bestgeeignetste und realitätsnächste Modell für derartige hochauflösende, räumlich magnetfeldorientierte Simulationen im Bereich der F–Schicht der Ionosphäre.
>
> (iii) Etwa vier Dutzend TID Ereignisse wurden durch sorgfältige Datenanalyse unter Berücksichtigung aller fundamentalen Ionosphärengrößen aus über vier Jahren EISCAT–Datenbasis herausgearbeitet und einer statistischen Studie des Amplituden– und Phasenverhaltens von TIDs unterzogen. Auf diese Weise wurde erstmals die typische empirische TID–"Polarisationsinformation" herausgearbeitet, die für AGW–verursachte TIDs in IS–Daten (für nicht–äquatoriale Breiten) zu erwarten ist. Die einzelnen analysierten TID Ereignisse sind darüberhinaus zum Vergleich mit Simulationen von großem Nutzen (und wurden z.T. ja auch diesbezüglich verwendet).

(iv) Für den praktisch sehr wichtigen Rückschluß von gemessenen Ionosphärendaten auf AGWs in der Thermosphäre wurde eine neue "inverse modeling"–Methode entwickelt und für verschiedene repräsentative TID Ereignisse in echten IS–Daten zur Deduktion umfassender quantitativer AGW–Information erfogreich eingesetzt. Wohingegen bisherige Methoden nur semi–quantitative Information über vereinzelte AGW–Parameter liefern konnten, kann die neue Methode konsistent die gesamte Polarisations– und Dispersionsinformation einer AGW am Ort des IS Meßstrahls liefern.

(v) Es wurden neben AGW/TIDs auch die Charakteristika anderer möglicher TID–Verursacherprozesse in Hohen Breiten mit Hilfe theoretischer Modellierung untersucht (insbes. Variationen der elektromagnetischen Drift, des superthermischen Teilcheneinfalls und von magnetfeldparallelen Strömen). Es wurden das physikalische Verständnis der mit diesen Mechanismen verbundenen TIDs vertieft und Charakteristika gefunden und herausgearbeitet, welche die Interpretation von TIDs in IS–Daten in Termen dieser Verursacherprozessen ermöglichen. Insbesondere wurden Kriterien für eine zuverlässige Erkennung der AGW/TIDs unter anderen TIDs angegeben.

(vi) Anhand der modellierten AGW/TID Fälle in IS–Daten konnten erstmals von AGWs verursachte TID Fälle zweifelsfrei anhand der Benützung von TID–Information entlang eines einzigen Meßstrahls nachgewiesen werden. Für die wenigen bisher eindeutig nachgewiesenen Fälle mußten unter beträchtlichem Aufwand zur Konstruktion klarer "Ausbreitungsinformation/Dispersionsinformation" Daten vieler Stationen kombiniert werden.

Figures 3 and 4 highlight selected results from the many ones, which led to these conclusions. Figure 3 illustrates a one-to-one comparison of simulated and observed TIDs. The simulations were performed with the GIFTS model plus an AGW model and the observations were gained with the EISCAT radar (near Tromsø, Norway), respectively. Results on all four fundamental plasma parameters n_e, v_i, T_i, and T_e are shown (both simulated and observed data bandpass-filtered for the wavelike signatures with a period of about 60 min). Figure 3 indicates that the prediction skill of the model is quite convincing; Phil J.S. Williams (Physics Dep., Univ. of Wales, U.K.), including the Figure in his review chapter on Tides, AGWs, and TIDs in the book of Kohl et al. (1996), termed it "a milestone in our interpretation of TIDs".

Figure 4 shows amplitude profiles of TIDs from a simulation study (Kirchengast, 1997) on the most important potential causative mechanisms of TID signatures in the high latitude F region. The mechanisms, each of which was modeled via a typical wave structure with a period of 60 min, included AGWs ("AGW case"), electric field variations ("EBD/WS case" and "EBD/EN case", two different typical horizontal plasma drift directions), particle precipitation variations ("PPR case"), and ionospheric return current variations ("IRC case"), respectively. Figure 4 indicates how different causative mechanisms produce different ionospheric responses; information, which in turn can be exploited for detection and attribution of causative mechanisms via these signatures.

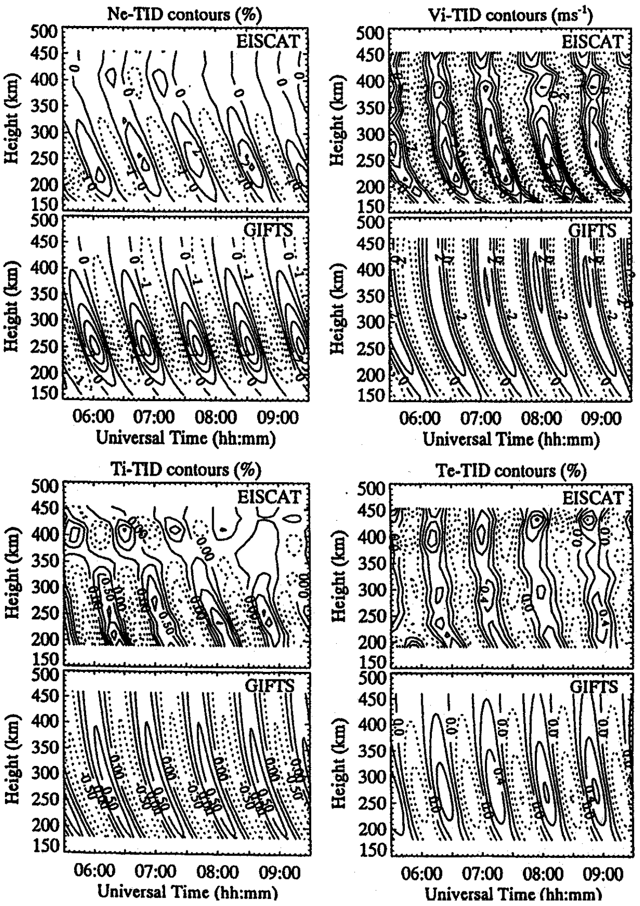

Figure 3: One–to–one comparison of modeling results (panels labeled "GIFTS") to EISCAT data (panels labeled "EISCAT") for a TID event on Aug 31, 1988. From Kirchengast et al. (1995a).

3.2 Ionospheric Tomography

Ionospheric tomography is concerned with the reconstruction of images of ionospheric electron density, most notably in the F region domain, from line-integral measurements such as Total Electron Content (TEC) data acquired from ground stations or from satellites.

Research in ionospheric tomography was performed at my Institute since the beginning of the nineties under the leadership of (and with the major contributions from) my colleague Reinhart Leitinger. I have been involved over the years, mainly until about 1996, in several different projects, ranging from early feasibility investigations (Leitinger et al., 1993) to the tomographic reconstruction of an electron density cross-section from a combination of real ground-based TEC data and real spaceborne ionospheric occultation data (Leitinger et al., 1997). The latter was, to my best knowledge, the first successful reconstruction published in the open literature, which was based on combined ground-based and spaceborne data. Other relevant work included (but was not limited to) the one of Rothleitner et al. (1994; 1995; 1996) and Leitinger et al. (1996).

As this area of research is well discussed by Reinhart Leitinger in his contribution to this "Festschrift", I will not go into further details here (see that article for more information).

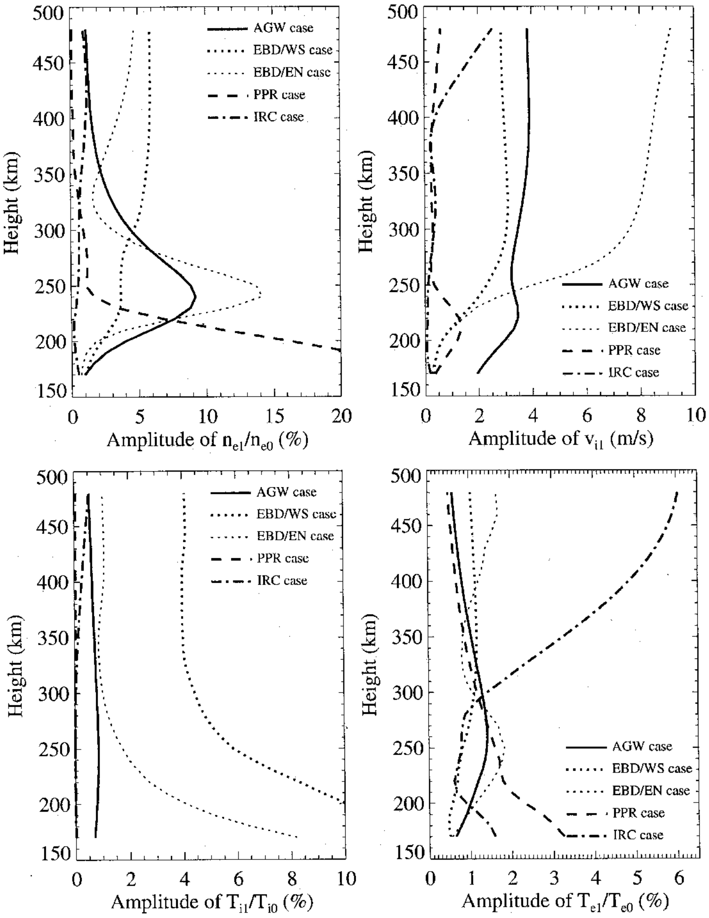

Figure 4: Amplitude profiles of TIDs for five representative cases of different causative mechanisms. Each panel compares, for one of the four fundamental plasma parameters accessible by incoherent scatter radars, the amplitudes of the five cases. From Kirchengast (1997).

4 Troposphere–Stratosphere–Ionosphere Sounding by Radio Occultation

4.1 Atmspheric Sounding by GNSS Radio Occultation

The atmospheric remote sensing research group, which I founded at the beginning of 1996, placed its initial research focus on GNSS radio occultation. The baseline work marking the way for this transition of mine from mainly working as a single researcher to working with a group, was reported in Høeg et al. (1995), Kirchengast and Ladreiter (1996), Ladreiter and Kirchengast (1996), and Bengtsson et al. (1996). This early work provided sufficient experience and insight to the topic (and, not least, international contacts) in order to start, together with a few bright young fellow scientists (and together with Reinhart Leitinger involved in ionospheric aspects), active participation in this rather new and exciting area of research at its leading edge.

Briefly summarized, Global Navigation Satellite System (GNSS) based radio occultation is an active atmospheric limb sounding technique, which is based on the tracking of the highly stable L–band signals (~1.2 GHz and ~1.6 GHz) of the U.S. Global Positioning

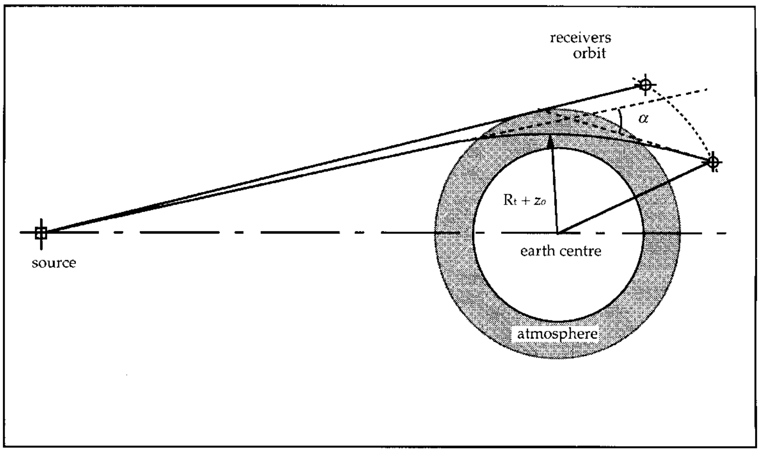

Figure 5: Sketch of the geometry of a GNSS radio occultation event. From Høeg et al. (1995).

System (GPS) and the Russian GLONASS system. (In a few years, this present GNSS system will hopefully be extended by the European Galileo system currently under preparation.) The method provides, as principal observable and with millimetric accuracy, the excess phase path (relative to propagation in vacuum) accrued by GNSS-transmitted radio waves due to refraction in the Earth's atmosphere and ionosphere. The latter is the basis for high quality retrievals of atmospheric key variables such as temperature, tropospheric water vapor, and ionospheric electron density. In terms of utility of the data, the method holds great promise for weather and climate as well as space weather research and applications in providing an unique combination of global coverage, high vertical resolution and accuracy, long-term stability, and all-weather capability. (The abstract of Kirchengast and Ladreiter (1996) provides a similar brief summary in German.)

Two Figures shall be used for illustration here, which admittedly look modest but which well mark the early times of relevant research in Europe (Russian and U.S. colleagues published early work already in the late eighties). Figure 5 shows the radio occultation geometry as sketched in Høeg et al. (1995), which was the first purely European scientific publication in the field. Figure 6 from Bengtsson et al. (1996), a work marking the kick-off of programmatic efforts for a European GNSS occultation mission, depicts results on the coverage with atmospheric and ionospheric profiles achievable for a given number of GNSS occultation sensors in a potential constellation. Figure 6 became (somewhat surprisingly) to play an important role in fostering acceptability of the GNSS occultation technique, and in particular of the idea of a constellation, at programmatic levels; I found it reappear later in several technical and managerial publications (e.g., GRAS-SAG, 1998). Its lasting core message, unexpected but highly welcome at the time when I produced it in 1996, was that only 6 to 12 satellites already provide rather favorable coverage compared to significantly higher numbers. Current plans for "demonstration constellations" to be installed in a few years in fact all rest on 6-to-12 satellite concepts (e.g., UCAR, 2000; see also Kirchengast et al., 1998; Steiner et al., 2000).

Further early publications from work in my group, which mostly addressed different critical GNSS occultation data analysis problems both in the atmosphere and ionosphere, include (among others) Hocke et al. (1997), Hocke (1997), Foelsche and Kirchengast

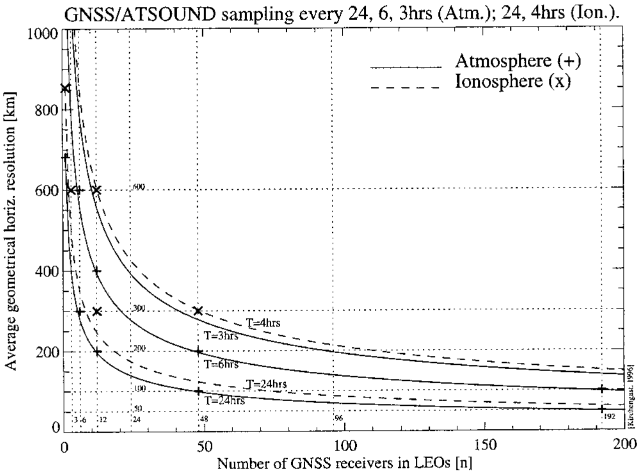

Figure 6: The dependence of average horizontal sampling distance ("geometrical horiz. resolution") on the size of a GNSS sensor constellation, given the time interval within which this sampling is to be globally achieved. From Bengtsson et al. (1996).

(1997), and Leitinger and Kirchengast (1997a). A significant part of the Ph.D. work of Steiner (1998) and Foelsche (1999) was performed during this time as well.

4.2 End-to-end Simulation of the GNSS Occultation Technique

A key achievement of my group, together with colleagues in an international European consortium, was the development of the so-called End-to-end GNSS Occultation Performance Simulator (EGOPS) within an ambitious scientific software project realized under my leadership; work which started in 1996 and which is still on-going. A description of the envisaged capabilities of EGOPS at project start was given by Kirchengast (1996e), a detailed overview including example applications after availability of EGOPS, Version 2, by Kirchengast (1998a), and a detailed "Software User Manual" of EGOPS, Version 3, by Ramsauer and Kirchengast (2000). Currently EGOPS, Version 4, is under development. According to Kirchengast (1998a) rationale and objectives for EGOPS can be summarized as follows (slightly updated):

> *Basic Rationale:* Given the promise of GNSS occultation science, a tool is highly desirable for integrated simulation of the GNSS-based radio occultation technique in an end-to-end manner — from the GNSS satellites transmitting the signals down to final data products like atmospheric profiles of temperature and water vapor.
>
> *Major Specific Objectives:*
>
> - *Mission Analysis and Planning* for generic satellites in Low Earth Orbits (LEOs) equipped with GNSS receivers (e.g., GRAS). Complementary add-on: Mission analysis and planning for GNSS scatterometry (ocean-reflections). — Geometry of occultation (reflection) events, coverage by events, various statistics for given GNSS/LEO/ground-station constellations and antennae field-of-views.
> - *Simulation of Occultation Observations* (forward and observation system modeling). — GNSS-to-LEO signal propagation through the atmosphere/-

ionosphere system plus effects of the observing system such as POD errors, antenna pattern, local multipath, receiver noise, and clock drifts.

- *Processing of simulated and observed occultation data* (inversion from phases and amplitudes to atmospheric/ionospheric profiles). — Data processing of the simulated observables as well as of real data, such as from GPS/MET, by a variety of different processing chains (including statistical optimization initialization, back-propagation techniques for tropospheric processing, etc.).
- *Integrated visualization/analysis of all simulator results.* — Statistical post–processing and visualization; geographic maps visualization; profiles post-processing, validation, and visualization; volume data visualization and animation.

Overall Objective: Effective treatment of all relevant aspects of GNSS occultation by an integrated, flexible, and user–friendly tool open for continuous improvements.

Figure 7 shows a conceptual model of EGOPS, well illustrating its functional components and their interplay. In order to illustrate the utility of the software by at least one example, Figure 8 shows a result of an empirical statistical analysis for the temperature profiling accuracy to be expected from the European GRAS (GNSS Receiver for Atmospheric Sounding) sensor. The results were obtained based on realistic end-to-end simulations of a representative ensemble of occultation events under EGOPS.

EGOPS has become in the meantime the most advanced tool in the area worldwide. Given this, it has also become the reference and performance benchmark for the development of operational processing systems for future missions such as for the GRAS sensor on the European weather satellite METOP. It is currently used by about a dozen different institutions in research and industry in Europe and worldwide for many different applications ranging from mission planning to scientific data analysis. In my group, we have as well employed EGOPS, or suitable components of it, for many different studies so far, including Kirchengast (1998b), Kirchengast and Ramsauer (1998; 1999), Ramsauer and Kirchengast (1999), Kirchengast et al. (2000), von Engeln et al. (1999; 2000), Foelsche and Kirchengast (2000b), Steiner et al. (2000), and Hartmann et al. (2000). It will be employed even more intensely in recently started and planned future studies.

Finally, three empirical atmospheric/ionospheric models developed in close connection with the EGOPS work deserve to be mentioned, which have been found of high utility for different studies within my Institute but also in a series of other institutions. These include a global empirical electron density model (Leitinger et al., 1996; see also Leitinger and Kirchengast, 1997b), an enhanced CIRA-86 moist atmospheric climatology model (Kirchengast et al., 1999), and a simple analytical atmospheric model for radio occultation applications (Kirchengast, 1999), respectively. The ionospheric model has been significantly extended and enhanced in the meantime by Reinhart Leitinger and colleagues; more details are found in his article in this “Festschrift”.

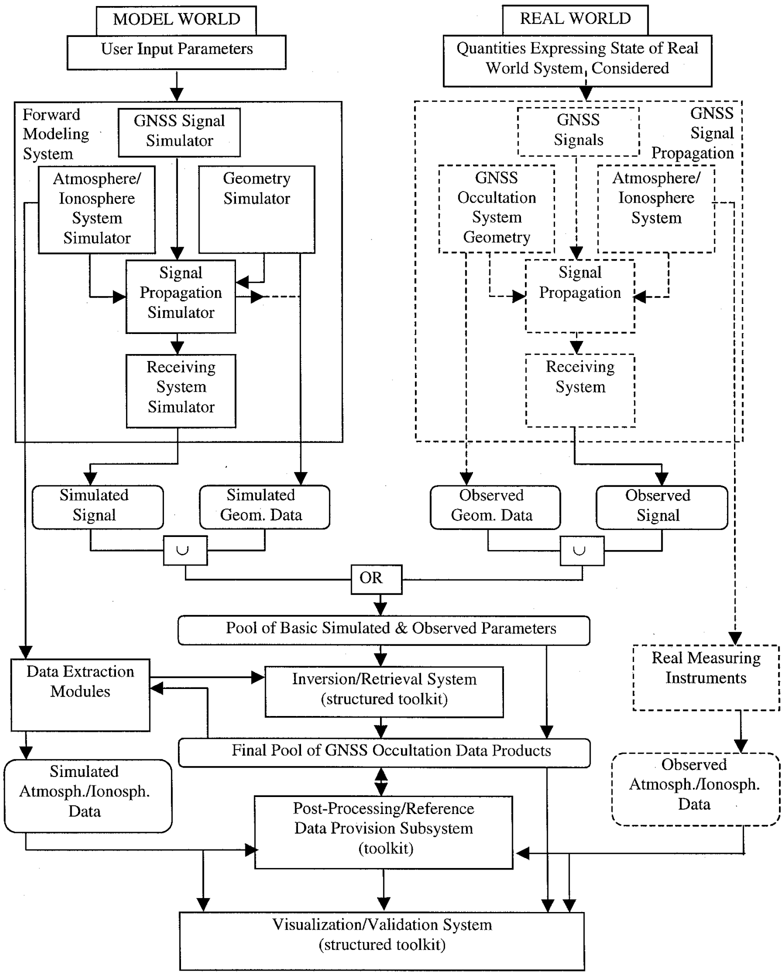

Figure 7: Conceptual view of the end-to-end modeling of all relevant aspects of GNSS radio occultation by EGOPS. From Ramsauer and Kirchengast (2000).

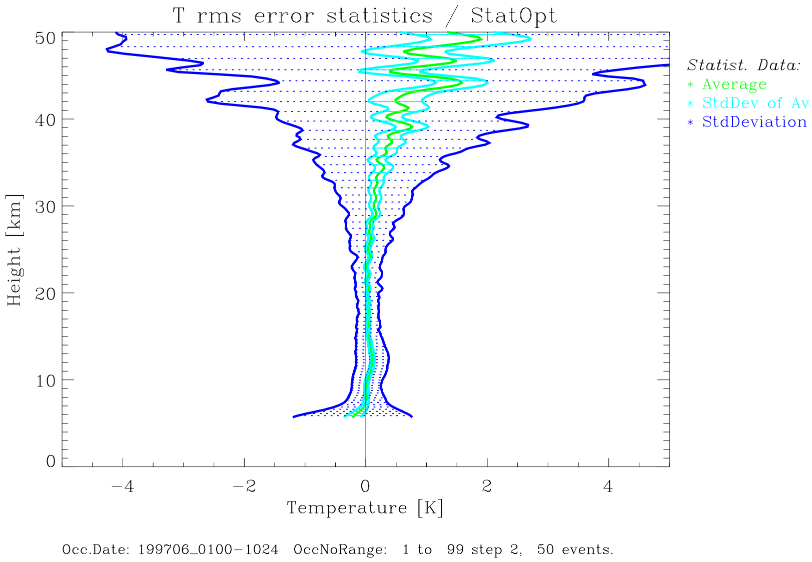

Figure 8: Temperature error statistics based on a representative ensemble of 50 occultation events of a GRAS–type sensor, showing the mean (green), the standard deviation (dark blue), and the error of the mean (light blue). From Steiner et al. (2000).

5 Troposphere–Stratosphere–Mesosphere Sounding and Climate Change Analysis

This title well circumscribes the core fields of research we follow in the Atmospheric Remote Sensing and Climate System (ARSCliSys) Research Group since about 2 years. We focus our research on the most promising satellite-based methods for obtaining atmospheric data of climatological utility, most notably (GNSS, stellar, solar) occultation methods and high-resolution infrared spectroradiometry. We also looked with success into microwave radiometry and ground-based GNSS sounding (see subsection 5.2). A reasonable view on the overall objectives of this research can be gained based on part of the Executive Summary of the proposal for an "atmosphere and climate sensors constellation" by Kirchengast et al. (1998) (somewhat adapted):

> The primary objective of the sounding research is to provide fundamental atmospheric data of unique quality for climate change research, especially on atmospheric change, which lies at the heart of concerns that the evolution of the Earth's climate system is increasingly influenced by human activities. This objective comprises climate analysis, monitoring, modeling, prediction, and process studies, all of which were significantly fostered by such fundamental data, most notably on temperature, water vapor, and ozone. For example, indications exist that the changing thermal structure from the upper tropo– to mesosphere is a particularly sensitive indicator of anthropogenic climatic impacts. The aim is to furnish data of sufficient quality to globally monitor this changing structure over the full troposphere/stratosphere/-mesosphere with unprecedented accuracy.
>
> Another main objective is to support atmospheric analysis and modeling such as currently performed for weather forecasting in the troposphere and lower stratosphere. To this end, unique data can be made available for significantly improving classical numerical weather prediction (NWP) but also for providing an unprecedented boost to NWP including the full middle atmosphere up to the mesopause (or even the upper atmosphere as well).
>
> A "spin-off" objective, from the point of view of the group's focus, is that the methods employed also provide unique observations for upper atmosphere (thermosphere/ionosphere) research, most notably ionospheric electron density (GNSS occultation) and thermospheric densities and temperature (solar occultation).
>
> The primary objective in exploiting the results of the sounding research is to investigate and assess the utility of the sensors studied as a long-term observing system for climate monitoring and climate and weather prediction of the entire (low/middle/upper) atmosphere. Within this broad objective, the focus is on using the data for climate change analysis in the tropo-/strato-/mesosphere.

Below I briefly survey relevant work performed and selected results obtained.

5.1 Temperature, Water Vapor, and Ozone Sounding by Occultation Methods

A significant contribution has been made to a better understanding of errors and to the validation of the GNSS radio occultation method by Steiner et al. (1999). Steiner

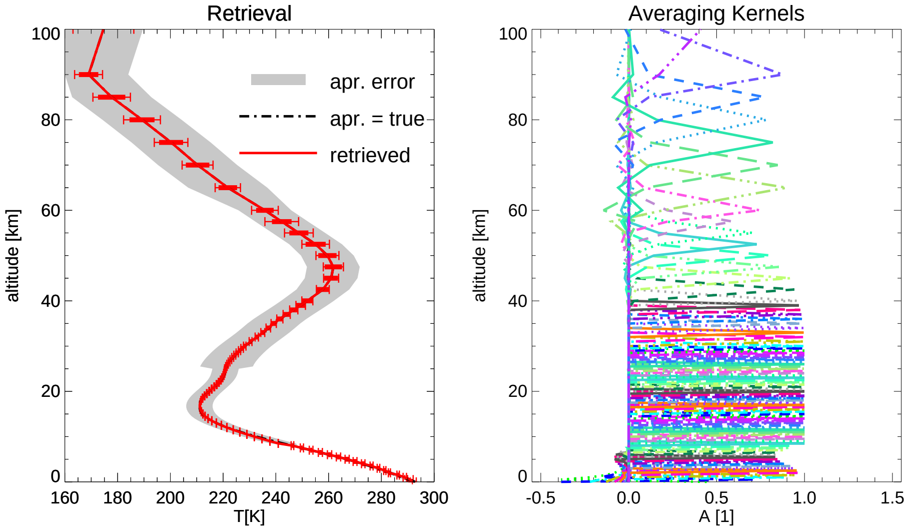

Figure 9: Typical mid-latitude temperature profile (left panel), and the corresponding averaging kernels indicating the resolution (right panel), retrieved by optimal estimation based on a combination of MAS and GRAS sensor data. Realistic measurement errors have been adopted for both sensors. From von Engeln et al. (1999).

and Kirchengast (2000) have provided the first analysis of gravity wave activity in the upper troposphere and lower stratosphere based on real GNSS occultation data. Further details related to these two papers are found in Steiner (1998) (Ph.D. thesis). Rieder and Kirchengast (2000c) performed a rigorous theoretical error analysis and characterization of the GNSS occultation data processing chain based on a Bayesian formalism. A summary on the capabilities of GNSS occultation, with focus on the troposphere, was given by Silvestrin et al. (1999). Von Engeln et al. (1999; 2000) and Hartmann et al. (2000) studied the optimal combination of GNSS occultation data with passive microwave limb sounder data for obtaining continuous temperature profiles from surface to mesopause.

As an (arbitrary) example of our many important results related to GNSS occultation, Figure 9 illustrates a combined optimal estimation retrieval of a temperature profile from surface up to the mesopause region. A GRAS-type sensor and a MAS-type (MAS, Millimeterwave Atmospheric Sounder) sensor were combined. The errors on the retrieved profile are less than 1 K up to about 35 km, where information from the GRAS sensor dominates, and are still within 4 K in the mesosphere, where the MAS sensor provides the essential information.

Work on absorptive occultations has been started as well. Based on the solar ultraviolet occultation sensor proposed by Kirchengast et al. (1998) (SMAS, Sun Monitor and Atmospheric Sounder), Rieder and Kirchengast (2000b) carried out a baseline analysis of the temperature profiling performance of such a SMAS-type sensor. The sensor promises to deliver an accuracy of better than 1 K at 2 km height resolution throughout the mesosphere. Rehrl (2000) (M.Sc. thesis) performed another baseline analysis for mesospheric temperature and ozone sounding by the SMAS sensor, also with promising results; the work is now advanced in form of a Ph.D. work of C. Rehrl. Work on stellar occultations for stratospheric temperature, ozone, and water vapor sounding is currently started in form of a Ph.D. work (C. Retscher) and a M.Sc. work (C. Bichler), respectively. It is related to the GOMOS (Global Ozone Monitoring by Occultation of Stars) sensor on the

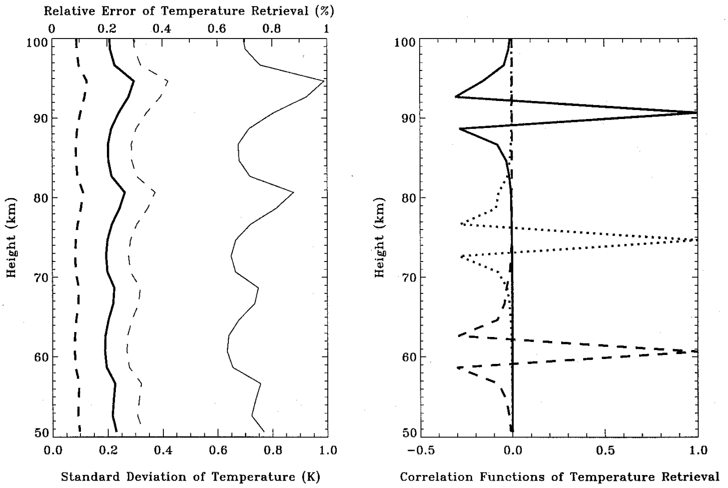

Figure 10: Temperature error results for an "advanced photodiodes" sensor (heavy lines) and a "standard photodiodes" sensor (light lines), respectively. Standard deviations (left panel) and error correlation functions at selected heights (right panel) are depicted; the latter do not depend on sensor scenario. From Rieder and Kirchengast (2000b).

European ENVISAT satellite to be launched in mid 2001.

An exemplary result of the absorptive occultation work is shown in Figure 10, which illustrates the baseline results for the temperature profiling performance of a SMAS-type sensor obtained by Rieder and Kirchengast (2000b). There is clear indication that the sensor can be expected to provide mesospheric temperature data of very favorable quality, which are highly complementary to data from GNSS occultation and stellar occultation sensors having their greatest sensitivity at lower heights.

5.2 Temperature and Water Vapor Sounding by Radiometric Methods and Water Vapor Tomography

The utility of existing operational microwave sounders for temperature and, in particular, humidity sounding was investigated by Rieder and Kirchengast (1999; 2000a); further details are also found in Rieder (1998) (Ph.D. thesis).
Lerner et al. (2000a; 2000b) and Weisz et al. (2000) provided promising initial results on the utility of high-resolution infrared spectroradiometry for temperature and humidity sounding. In particular, they studied the performance of the Infrared Atmospheric Sounding Interferometer (IASI) foreseen on the European METOP satellites.
Foelsche and Kirchengast (2000a) investigated the utility of a combination of ground-based and spaceborne GNSS sounding data for tropospheric water vapor imaging; further details on this work are given by Foelsche (1999) (Ph.D. thesis). As a "by-product" of the latter work, a simple and elegant new mapping function for the hydrostatic delay at GNSS frequencies was developed (Foelsche and Kirchengast, 2000b).

In order to provide at least a glimpse on the good results of these activities, Figures 11 and 12 illustrate examples, both based on fairly realistic atmospheric data from high-resolution weather analyses of the European Centre for Medium-range Weather Forecasts (ECMWF).

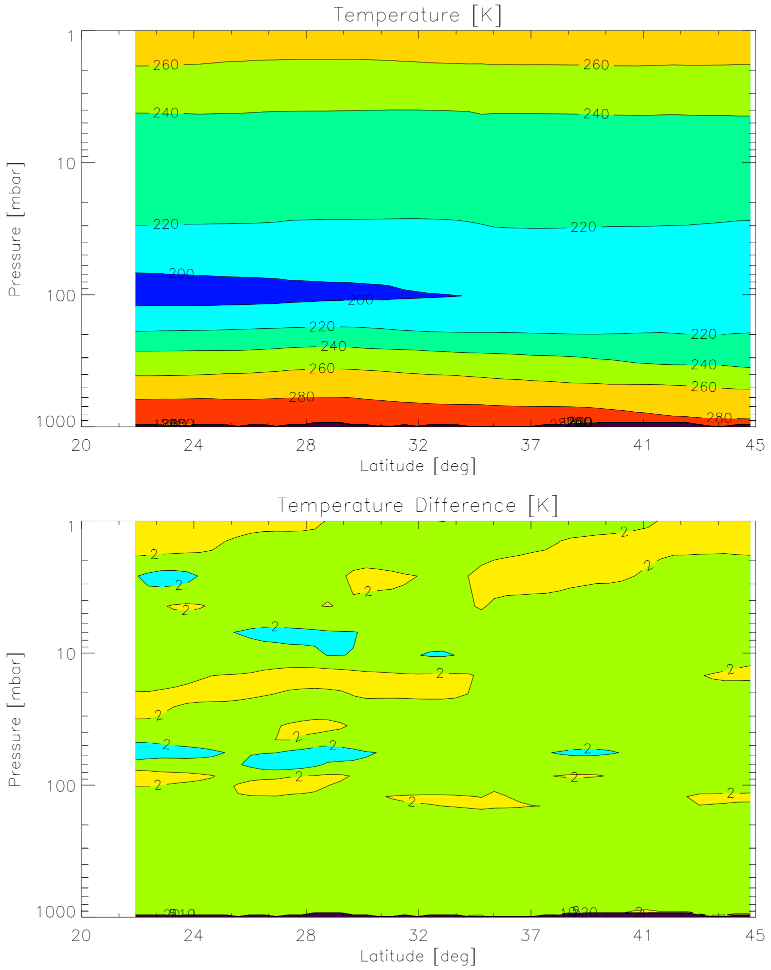

Figure 11: IASI temperature retrieval performance test for a meridional slice of mid-latitude weather analysis data. The retrieved temperature field (upper panel) and the difference of the retrieved and the "true" field (lower panel) are shown, respectively. From Weisz et al. (2000).

Figure 11 shows results for a temperature field retrieved from simulated clear-air IASI spectra with realistic measurement errors superposed. The difference field (lower panel) indicates that the IASI sensor shows particular promise in the troposphere; closer inspection points to best performance in the middle and upper troposphere. This is a very favorable characteristic, since accurate data on the upper tropospheric moisture distribution are among the most needed observations in climate change research. Figure 12 shows an exemplary case of a reconstructed tropospheric water vapor cross-section compared to the "true" water vapor field in a one–to–one manner. The Figure indicates that the secondary water vapor maximum at a height of ~3 km, associated with the boundary of the tradewind inversion, is well resolved in the reconstruction.

5.3 Advanced Spaceborne Sounding and Climate Change Analysis

Two ambitious projects are currently on-going in the field of investigating and enhancing the utility of data from the sounding methods addressed above for observing climatic changes in temperature, humidity, and ozone fields of the tropo-/strato-/mesosphere. The

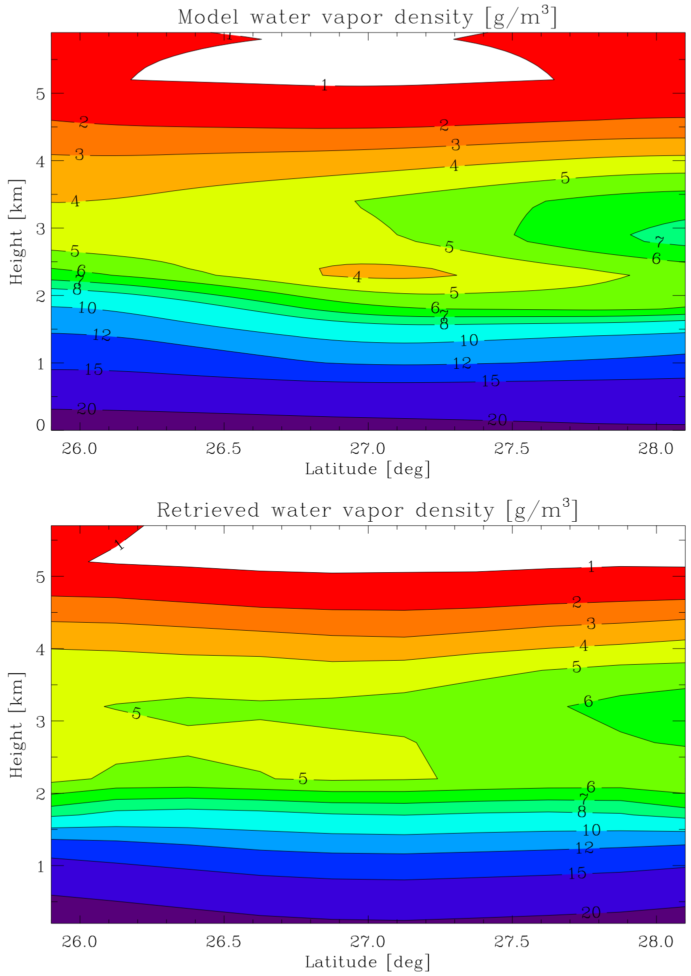

Figure 12: Comparison of a "true" water vapor density field (upper panel) with the field reconstructed by an optimal estimation method (lower panel). The model data are weather analysis data over Florida, U.S.A. From Foelsche and Kirchengast (2000a).

already quite advanced one is concerned with the utility of GNSS occultation data for climate monitoring (Kirchengast et al., 2000; Steiner et al., 2000). Another one on methodologies for optimal fusion of the data from different sensors, especially of occultation data and selected IASI data, into coherent global monthly climatologies of temperature, humidity, and ozone fields was recently started and is mainly the subject of a Ph.D. work of G. Otto.

The introductory paragraph to the "Study design" section in Kirchengast et al. (2000) provides an idea on the scope of the first project noted (slightly adapted):

> Based on an approach, which can be termed a "climate observing system simulation experiment", we perform a rigorous quantitative test of the climate change detection capability of GNSS occultation sensors by an integrated analysis involving five main parts of work as follows.
> (i) Realistic modeling of the atmosphere (neutral atmosphere and ionosphere) over the time period 2000 to 2025.
> (ii) Realistic simulations of occultation observables (i.p. of excess phase path profiles) for a small constellation of GNSS occultation sensors for 2001 to 2025 (25 years).

> (iii) State-of-the-art data processing for temperature profile retrieval in the troposphere and stratosphere to establish a sufficient database of realistic simulated temperature measurements for the 25 year study period.
> (iv) A multivariate statistical analysis of temperature trends in both the "measured" climatology based on the database of simulated measurements and the "true" climatology from the atmosphere modeling.
> (v) An assessment, by statistical inference, of whether and to what degree the GNSS occultation observing system is able to detect anthropogenic climatic trends in the atmospheric evolution.

Figure 13 illustrates, as an example of intermediate results of this study, the typical "sampling error" incurred due to the necessity of using the occultation data in form of seasonal averages within statistical bins spanning areas of about 10 deg latitude x 20 deg longitude. Favorably, this "sampling error" is below 0.5 K in most of the domain of interest. This is also true for the "instrumental (bias) error" as Figure 8 above indicates. These results are thus encouraging regarding the potential climate utility of GNSS occultation data, e.g., for reliably detecting (anthropogenically induced) temperature trends within less than the next two decades.

6 Outlook

This outlook is partitioned for convenience into two parts, one looking (seriously) into the more immediate future until 2004, the other looking (less seriously) a little bit into the time beyond.

6.1 The Next Few Years

A series of projects is currently on-going (or rather firmly planned already) for the time range until 2004. All of these fall into the realm of the broad general objectives of my research group outlined at the beginning of Section 5. More concrete work objectives for the next few years were reasonably summarized in the introduction of a recent proposal of mine on the exploitation of ENVISAT data (in German, somewhat adjusted):

> Das übergeordnete wissenschaftliche Ziel ist die Untersuchung des Potentials von in naher Zukunft (auf ENVISAT) erstmals in der Praxis getesteten innovativen Satellitenfernerkundungs–Sensoren für globales Monitoring des Klimawandels in der Atmosphäre im Kontext von methodisch verwandten neuartigen Sensoren mit hohem Synergiepotential.
>
> Die diesen interessierenden Sensoren zugrundeliegenden Methoden sind die Okkultationsmethode und die hochauflösende Infrarot–Spektroradiometrie. Es scheint mit diesen Methoden möglich, die Änderungen in der Atmosphäre auf der Skala von Jahreszeiten bis Jahrzehnten in den Fundamentalparametern Temperatur, Wasserdampf und Ozon — die wichtigsten Parameter hinsichtlich Klimawandel — mit einer Genauigkeit und Auflösung zu messen, welche mit keiner anderen bekannten Methode erzielbar ist. Kann dieses Potential tatsächlich nachgewiesen werden,

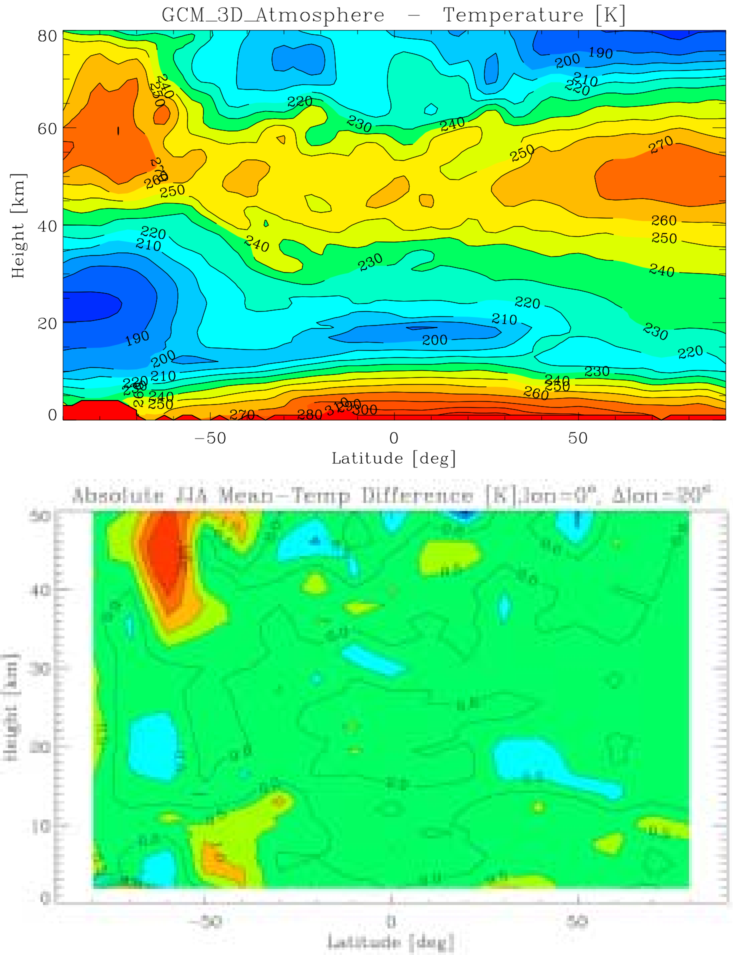

Figure 13: Typical latitude-height temperature slice produced for a single time layer by the MAECHAM T42L39 climate model of the MPI for Meteorology, Hamburg, Germany (upper panel), and slice exhibiting the "sampling error" due to collecting a limited number of profiles over a full season of time layers and over spatially extended bins (lower panel). From Steiner et al. (2000).

eröffnet dies eine völlig neue Ära etwa für das Verständnis des menschgemachten Klimawandels durch Treibhausgasemissionen und das operationelle Monitoring der verursachten atmosphärischen Änderungen.

Die interessierenden Sensoren auf ENVISAT sind der GOMOS–Sensor (Stern–Okkultationsmethode) und der MIPAS–Sensor (interferometrische Infrarot–Limbsondierung). Die interessierenden verwandten Satellitensensoren, die sehr hohen synergetischen Nutzen versprechen, sind GNSS–Okkultationssensoren wie das auf METOP vorgesehene GRAS-Instrument (Radio–Okkultationsmethode / GNSS Limbsondierung), Sonnen–Okkultationssensoren wie das der ESA vorgeschlagene SMAS–Instrument (Solar–Okkultationsmethode) und Infrarot–Spektroradiometer wie das auf METOP vorgesehene IASI–Instrument (interferometrische Infrarot–Nadirsondierung).

In der ARSCliSys–Arbeitsgruppe werden bereits Studien zu den GRAS–, SMAS–, und IASI–Sensoren durchgeführt, welche durch Studien zu den GOMOS– und MIPAS–Sensoren und zum Synergiepotential mit den erstgenannten Instrumenten ergänzt werden sollen, insbesondere mit den Okkultationssensoren. Den Kern

> aller wissenschaftlichen Bemühungen sollen klimaphysikalische Studien unter bestmöglicher Nutzung der Satellitendaten bilden. Diese sollen, dem eingangs erwähnten übergeordneten Ziel entsprechend, realistische quantitative Aussagen zu den Möglichkeiten und Grenzen des Klimawandel–Monitorings mithilfe von Okkultationsmethoden und hochauflösender Infrarot–Spektroradiometrie liefern.

Similar information in English and further more detailed information on the group and its activities is available on-line via http://www.kfunigraz.ac.at/igam/arsclisys.

In addition to the science objectives, I consider the prospering of my research group in terms of off–springs as another important objective. In a few years, bright Post-docs from within the group may have reached a level of professional maturity so that they found their own groups in their most favorite areas of scientific interest (either at our Institute or elsewhere). I look forward to such a gratifying signal for the scientific creativity and liveliness of the group.

6.2 2005 and Beyond

This is the time, where the fruits of the recent efforts and those of the next few years are to be harvested. As the details of the harvest are quite uncertain, however, there is convenient room for (optimistic) visions. I like to offer in passing two of my favorite visions for my group and my Institute (assuming myself still being part of them).

The first vision is on the bright future of occultations, nominally becoming true within the 2005 to 2010 timeframe: Not least based on the fruits of the on-going and upcoming research of the ARSCliSys group, a constellation of 6 to 12 microsatellites carrying GNSS (including Galileo), stellar, and solar occultation sensors will continuously deliver fundamental atmospheric data of unprecedented quality for the entire atmospheric domain. The mission will become the authoritative backbone of the Global Climate Observing System (see http://www.wmo.ch, link GCOS, for details) for climate change monitoring, and in addition provide many further benefits to atmospheric and climate system physics as well as to applied areas such as operational meteorology and space weather services. The role of the Institute is, given its merits, obvious in this context: It is one of the top science centers in the field and it is operating (on behalf of the European Union and other international institutions) an affiliated Data and Services Center for this GCOS core mission to be maintained over decades. The latter Center, in charge of data and support services for the scientific user community worldwide, provides about 20 exciting positions for qualified (young) scientists interested in applied research.

The second vision is on a "Center for Climate Change Research and Policy", nominally becoming true within 2005 to 2010 as well: Having achieved worldwide reputation for the contributions of its ARSCliSys group to climate change monitoring and analysis, the Institute founds, together with other Institutes at the University with competence in the field ("Institut für Volkswirtschaft", etc.), a Center as quoted above. Its main missions include (i) Monitoring and analysis of climate change, (ii) Regional impacts of global climate change, and (iii) Climate protection policy analysis and advice. It is the leading competence center of this sort in Austria and among the top ones within the European

Union, much needed at that time to come. In terms of staff it provides about 20 to 50 exciting positions for qualified (young and senior) scientists interested either in basic or applied research.

Let me stress that these are just exemplary visions (rather arbitrarily selected from a pool of distinctly bold visions). The future may thus lead, more likely than not, the ARSCliSys group and the Institute towards entirely different activities. This is equally fine with me. What I sincerely wish, however, is that both may flourish as well over the next 10 years as they could during the 10 years gone under the sensible and far-sighted direction of the Institute by Prof. Siegfried Bauer and, since recently, by Prof. Reinhart Leitinger. Happy Birthday!

Acknowledgments: Together with Siegfried Bauer and Reinhart Leitinger, to whom this article is dedicated (see abstract), many other people deserve to be appreciated.
I honestly thank all colleagues, from within my Institute as well as from elsewhere, for the co-operativeness, support, advice, encouragement, and even friendship, they have given to me over the years addressed by this review. They are too numerous to be all named here in person, but many thanks indeed shall go to each one of them. Special thanks go to all my co-authors on common publications, in particular to the leading co-authors (first authors) who generally invested the major efforts into the papers concerned. I am glad to see essentially all of them explicitly appreciated in that their names appear in the list of references below.
I wish to thank and acknowledge in person the members of my research group (status Oct 2000): Andrea Steiner, Elisabeth Weisz, Christoph Bichler, Ulrich Foelsche, Heinrich Grillhofer, Jeffrey Lerner, Gustav Otto, Werner Poetzi, Josef Ramsauer, Christoph Rehrl, Christian Retscher, and Markus Rieder (ex officio). They play(ed) key roles in recent and on-going research projects, which in fact could not be carried out without their dedication. Related to this, I am also much indebted to all sponsors of our research (none of these young scientists holds a permanent university position), especially to the Fond zur Förderung der wissenschaftlichen Forschung (FWF, Vienna, Austria) providing the funds for the START research award I received in 1998 and to the European Space Agency's Space Research and Technology Centre (ESA/ESTEC, Noordwijk, Netherlands); the K.u.M. Kaufmann Foundation, Graz, Austria, was of pivotal help in the initial phase after founding the group in 1996.
Last but not least, I express my deep gratitude and sincere respect to my wife Anna, who in fact deserves honorary co-authorship for many of the publications I have (co-)authored; way too often she had to generously replace me in non-scientific duties due to my frequent return from work at totally inappropriate times. This article could simply not have been written, due to lack of publications to survey, without her continuous support and understanding.

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