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GREAT – The First-Generation German Heterodyne Receiver For SOFIA

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ABSTRACT

A consortium of German research laboratories has been established for the development of a modular dual-channel heterodyne instrument (GREAT: *German Receiver for Astronomy at Terahertz Frequencies*) for high-resolution spectroscopy aboard SOFIA. The receiver is scheduled to be available in time for SOFIA´s very first astronomical missions in late 2002. The first-flight version will offer opportunities for parallel observations in two frequency bands. We will have a choice of backends, including an acousto-optic array (4x1GHz) and a high-resolution chirp transform spectrometer.

The modularity of the system permits the perspective of later upgrades and – with time – of an increasingly more complete coverage of the FIR-spectral range. Our first version will focus on three scientifically selected frequency bands, covering the astrophysically important fine-structure transition of ionized atomic carbon (1.9 THz), the ground-state transiton of deuterated molecular hydrogen (HD) at 2.6 THz, and the fine-structure line of neutral atomic oxygen, [OI], at 4.7 THz.

Keywords: far-infrared, submillimeter, heterodyne receiver, hot electron bolometer, SOFIA

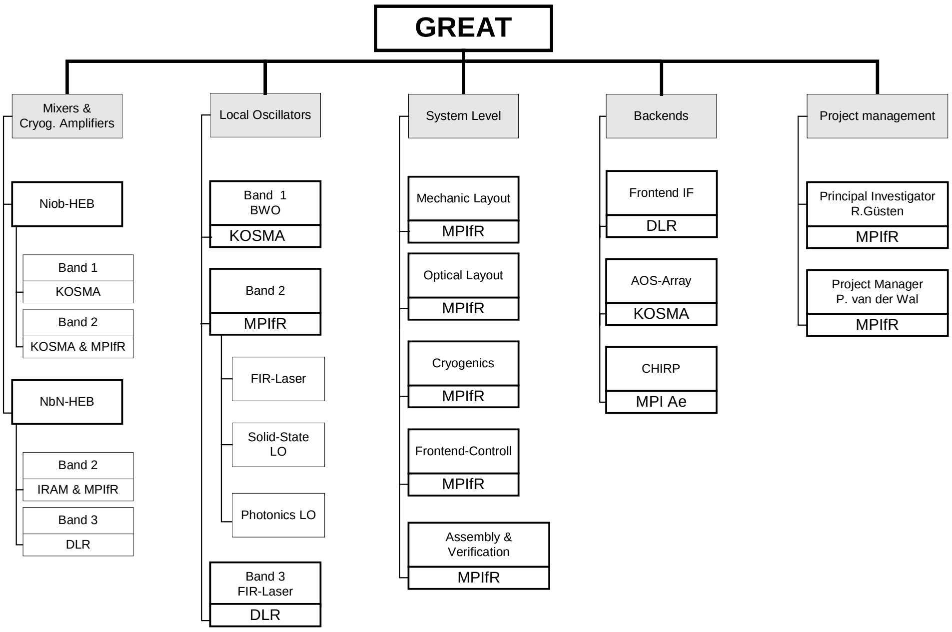
1. INTRODUCTION

There is great scientific demand in high-resolution spectroscopy at Terahertz frequencies. Spectral resolution, $R = \lambda/\Delta\lambda$, of order 10^{6-7} is required to address a wide range of topics of modern astrophysics, from questions about planetary atmospheres and the interstellar medium in the Galaxy to investigations related to the early Universe. Often, high resolution is crucial to discriminate a given interstellar line against narrow atmospheric absorption features (see Fig.2, for the case of the HD line). With the impressive progress in detector technology over the recent years, the development of sensitive heterodyne receivers for the Terahertz spectral range has now become possible.

A consortium between the MPI für Radioastronomie, the I.Physikalisches Institut der Universität zu Köln (KOSMA), the DLR-Institut für Weltraumsensorik & Planetenerkundung and the MPI für Aeronomie has been established for the development of *GREAT (German Receiver for Astronomy at Terahertz Frequencies*), a dual-channel heterodyne instrument for high resolution spectroscopy aboard SOFIA. This first-generation instrument is scheduled to be available in time for SOFIA´s first astronomical missions in late 2002. The modularity of the receiver design will potentially, and in the long run, allow an increasingly more complete coverage of the FIR spectrum. Because of the RF-limitations inherent to the individual modules ($\Delta\nu/\nu$ ~10%), our first flight version will have to focus on three scientifically-selected frequency windows:

- a low-frequency band, 1.6–1.9 THz, covering – among other lines - the important atomic fine-structure transition of ionized carbon [responsible: KOSMA];
- a mid-frequency detector, centered on the cosmologically relevant 1-0 transition of deuterated molecular hydrogen (HD) at 2.6 THz and the rotational ground-state transition of OH($^2\Pi_{3/2}$) [MPIfR];
- a high-frequency channel that targets at, e.g., the 63μm fine-structure transition of atomic oxygen [DLR].

The project manager is Peter van der Wal (MPIfR). The MPIfR is responsible for the overall system design and configuration, mechanical layout, final assembly, integration and verification. The individual detector chains will be provided by the collaborating institutes. Fig.1 presents a breakdown of responsibilities on component level:



2. SCIENTIFIC MOTIVATION

We briefly emphasize a few scientific highlights that will be studied with GREAT aboard SOFIA. It would not be possible to address any of these scientific questions from ground-based observatories because of the large opacity of the atmosphere. SOFIA therefore will provide unique research opportunities.

Science in the low-frequency band: this frequency range is selected because it covers the most important cooling line of the interstellar medium, the [CII] 158 µm fine-structure transition, both in galactic sources and in moderately redshifted external galaxies. Beyond a few first observations[1] with the – at that time – relatively poor sensitivity of Schottky heterodyne receivers on the KAO, no observations of this important transition with a velocity resolution adequate to reveal the internal dynamical structure of the interstellar gas are available. Up to now detailed studies in the [CII] line have concentrated on the strong emission from massive star forming regions, where ionized carbon is abundant and easily excited in the photo-dissociated surface layers of molecular cloud clumps. There is good evidence, however, that a substantial fraction of the [CII] flux of a galaxy as a whole originates in more extended weak emission, presumably from a less dense gas illuminated by the average interstellar radiation field. Detailed assignment of various emission components in the [CII] line requires full velocity resolution in order to disentangle different emission components overlapping along the line-of-sight. The RF-tuning range will allow the study of galaxies up to redshifts of 50.000 km/s, with an angular resolution of 12”, which nicely matches to studies in complementary tracers obtained for comparison with large submm- and mm-wave ground-based telescopes. In practice, however, even at the flight altitude of SOFIA, some velocity intervals will be blocked by atmospheric absorption and will be assessable only with the heterodyne instrument (HIFI) on the FIRST satellite (launch in 2007). Although largely stimulated by the astrophysical importance of the [CII] emission, this frequency channel of GREAT may of course also be used to observe any other interesting line within its frequency band, such as the high-J rotational lines of CO and several light hydride transitions.

Science in the mid-frequency band: ever since the very first Big Bang nucleosynthesis models, the significance of the *cosmological* deuterium abundance for confining the baryon density of the Universe has been pointed out. Because of difficulties with the observational determination and due to uncertainties about the effects of chemical evolution (deuterium is easily "astrated" when processed through stars), the exact value of the primordial deuterium abundance, $[D/H]_{BB}$, remains uncertain. The astration factor is difficult to predict and very model dependent, but deuterium depletion may be as large as an order of magnitude. Observations of the 112µm ground-state rotational transition of the deuterated hydrogen molecule, HD, with SOFIA will allow the derivation of the abundance profile of deuterium across the Galactic disk and nearby galaxies, thereby providing critical information on the star formation history of these systems. In comparison with other metallicity tracers chemical evolution will be confined.

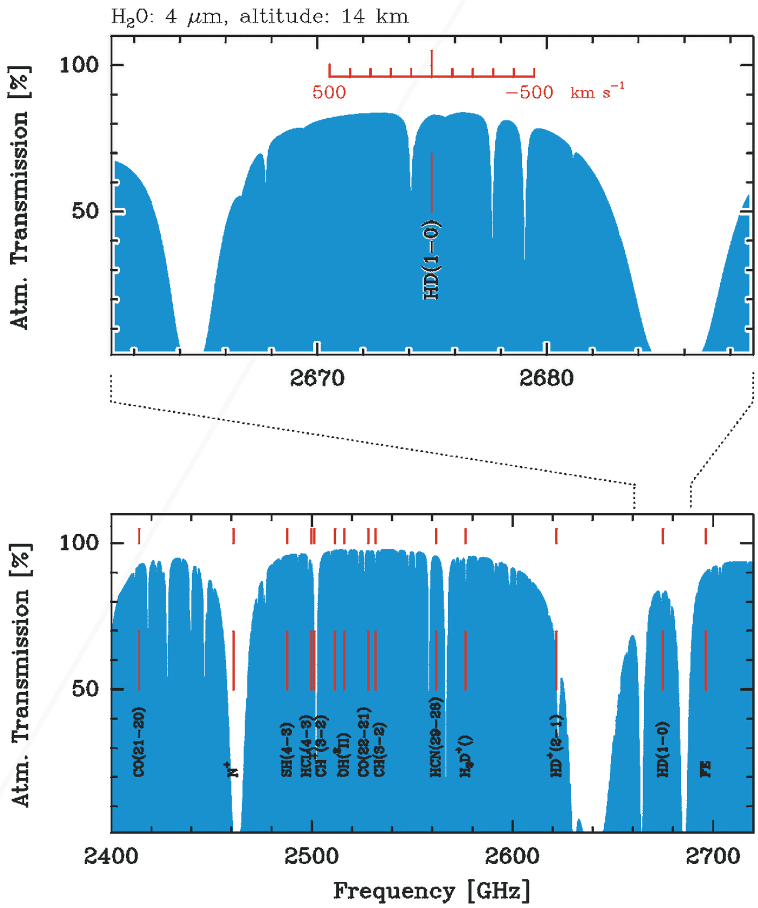


Figure 2: Atmospheric transmission as calculated for a SOFIA flight altitude of 14 km and 4.0µm zenith H_2O. Rest frequencies for a selection of astronomically relevant atomic and molecular transitions are labeled.The top panel displays a blow up of the atmospheric transmission close to the important HD(1-0) line. For reference, a velocity scale is superposed. Obviously, high spectral resolution is mandatory to discriminate any HD emission against narrow atmospheric absorption features.

While there are many astrophysically relevant transitions in this window (Fig.2), the fundamental OH $^2\Pi_{3/2}$ J=3/2 doublet at 119 µm is of special interest. The hydroxyl radical is one of the most important molecules in interstellar chemistry. It is vital for understanding the water chemistry, since it is both a precursor of water production and a product of water destruction. As the simplest oxygen-bearing molecule and being chemically very reactive, OH enters into the chemical networks for all other oxygen-bearing molecules, including CO and O_2. OH observations will be used to derive information about shocked molecular gas and will allow to discriminate between different shock models.

Our models on photo-dissociation regions (PDRs) will nicely be constrained by observations of the fine-structure line of neutral atomic oxygen, [OI], which at 4.7 THz is the main target of the high-frequency channel in GREAT. Atomic oxygen, via its fine-structure lines in the far-infrared, is a major coolant of the dense interstellar medium, and is a vital tool for probing the physical conditions (such as the density and the FUV radiation field) in the dense PDR layers around, e.g., massive young stars.

3. CONCEPT OVERVIEW

Our development goal is to provide a flight-qualified heterodyne instrument for high-resolution THz spectroscopy in time for SOFIA´s first astronomical openings (in late 2002). The system should be modular and flexible, with maximum sensitivity, IF-bandwidth and RF-tunability in scientifically-selected frequency bands. Within the financial envelope available, the consortium will develop a **dual-port receiver** for parallel observations at two frequencies**.** The instrument will consist of:

- a front-end unit with 2 independent cryogenic dewars, mounted to the telescope flange via a common “optics box” with the L.O. diplexers, the polarization splitter, the calibration unit and (optionally) a single-sideband filter. The mixers will be diffusion-cooled Nb or lattice-cooled NbN hot electron bolometers, depending on performance.

- a choice of backends, including an acousto-optical array spectrometer with 4 x 1 GHz wide bands (1 MHz spectral resolution) and an ultrahigh-resolution *chirp* transform spectrometer (180 MHz, 4096 channels).

- a data acquisition system customized to the needs of THz airborne spectroscopy.

The modularity of the receiver design allows easy changeover between different mixers and L.O. units covering different frequency bands. This makes GREAT a very versatile instrument, able to expand over the years to give a more and more complete frequency coverage of the FIR spectral range.

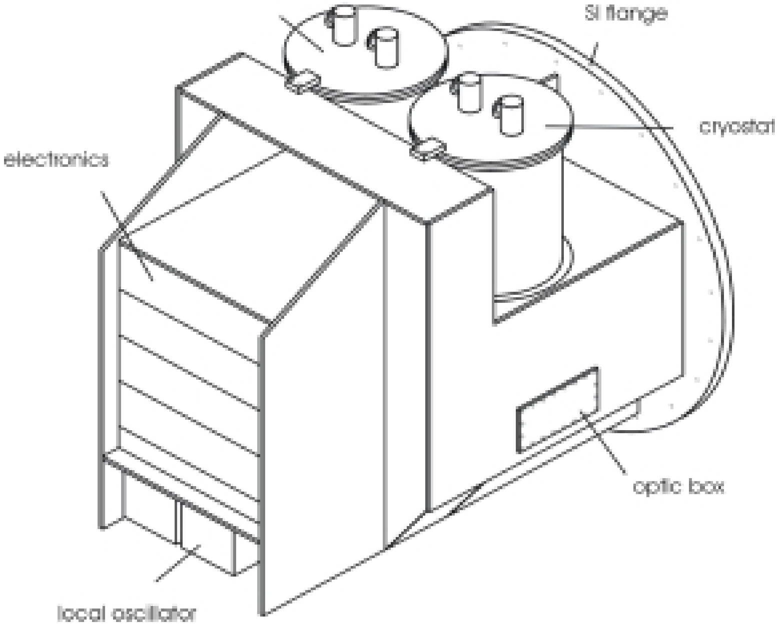


Figure 3. Structural layout of the GREAT front-end, displaying the science instrument flange, the two cryostats, the “optics box” hosting the beamsplitter and L.O. couplers, racks with control electronics and the local oscillators.

The design of the mechanical structure and of the cryostat is almost complete; special attention has been given to potential safety hazards aboard the aircraft. To conform with airworthiness requirements (most critically here, the response of the structure to emergency landing loads), detailed structural analysis was performed in collaboration with Prof. Hallmann (FH Köln, Fachbereich Maschinenbau), an expert with finite-element models. The cryostat is designed for a minimum hold time of 24 hours, and will contain about 3 Ltr of liquid ^{4}He.

Again, in the interest of safety, the design does take into account the (unlikely) event of a cryostat failure (maybe due to a structural failure or due to the blockage of the boil-off vent).

A basic requirement is that the instrument be modular and flexible: during flight we want to operate at two frequencies simultaneously, and between flights the change of cryostats and the replacement of optical components must be easy and straightforward. With a beam waist of only 1.7 mm (at 2.6 THz), this asks for precise mechanical tolerances to maintain the optical alignment.

We have started a development program on critical optical components for use at THz frequencies, such as wideband low-loss diplexers.

The availability of local oscillator (L.O.) power across an as wide as possible range of RF-frequencies ($\Delta\nu/\nu$ ~10-20%, for each frequency band) is a serious, but not a very critical issue. In fact, because unlike the requirements for a space mission like the HIFI (FIRST) instrument, aboard SOFIA we can tolerate mechanical tuners and even – relatively – high-power supplies. Therefore we have a choice of different technologies:

FIR-laser L.O.: optically pumped FIR ring lasers are in operation in the submm laboratories of all the collaborating institutes. An earlier version (MPIfR) has been flown successfully aboard the KAO. A laser L.O. consists of 2 lasers in tandem, with the FIR laser excited by the (9-10μm) CO_2 pump laser. Operation is reliable and, with appropriate stabilization loops, total power and frequency stability is good. However, obviously, this type of L.O. is not continuously tunable and the necessity of finding a sufficiently strong laser line near the observing frequency is potentially a limit for our flexibility in RF- and IF-coverage (although, for the most interesting transitions under discussion, suitable laser lines have been operated already; for other frequencies this has yet to be demonstrated). The existing instruments need upgrade to match airworthiness specifications. FIR-lasers LOs are the baseline option for the high-frequency band and the fallback source at lower frequencies.
BWOs: KOSMA is actively developing THz frequency sources based on backward wave oscillators. BWOs provide high output power at submillimeter frequencies (up to several tens of mW at 600 GHz) and can be phase locked to achieve excellent frequency stability. There are essentially two ways as to how BWOs can act as very attractive sources for THz power: direct frequency multiplication is most efficient, when starting from a high power, high frequency fundamental oscillator. Alternatively, BWOs can be mixed with optically pumped FIR lasers. The laser sidebands generated in this way, have the full tunability of the BWO but reach up to the high frequencies obtainable with the laser. Both these techniques have been successfully applied in lab spectroscopy over the last few years. There is no doubt that they can be further developed to provide local oscillators for heterodyne instruments. BWOs are of operational complexity similar to that of FIR lasers. We continue the development of both these options to cover the case that the high frequency solid state local oscillators may not be available for the very first SOFIA flights and in preparation of the STAR array detector[3], which power requirements are even more demanding.
Solid-state L.O.: the development of tunable “high”-power solid-state L.O.s is rapidly advancing into the THz regime, heavily stimulated by HIFI/FIRST related R&D[8]. A most likely scenario will be based on GaAs p-HEMT MMIC power amplifiers, operating in the range of 75-100 GHz that feed a chain of submillimeter-wave frequency multipliers.
Photonic L.O.: this relatively new technique to create local oscillator power at THz frequencies through optical mixing on a fast photodetector of two laser signals is investigated in collaboration with the Prof. P. Kordos (Research Centre Jülich), working on low-temperature grown GaAs substrates. Pioneering work at MIT Lincoln Lab[10] has produced photomixers with THz bandwidth, but with overall rather low quantum efficiency.

For GREAT we are pursuing all these L.O. options in parallel. As backup and safety option, the existing FIR-ring laser will have to be FAA-certified. But we expect that within the next 1-2 years, solid-state local oscillators will become available with sufficient power to service one (or two) HEB mixers, maybe with compromises on the RF-tunability. We aim at photonic L.O.s for our second-generation instruments.

4. SUPERCONDUCTING HETERODYNE DETECTORS

Many of the scientific breakthroughs of modern mm/submm astronomy have become possible only due to the rapid progress in the development of superconducting detectors. Mixers using *Superconductor Isolator Superconductor (SIS)* tunnel junctions have been constructed that perform with noise equivalents of a few times the quantum limit at frequencies below ~700 GHz, the gap frequency of niobium. At higher frequencies losses in the superconducting material rapidly degrade the performance. By using different materials (e.g., NbTiN), this cut-off may be shifted to slightly above 1.2 THz - for much higher frequencies current developments focus on a different type of device, so-called *hot electron bolometer* mixers. In a bolometric detector, the mixing relies on the strong temperature dependence of the resistance of a superconducting microbridge (bias point in the superconducting-normal state transition layer). The output reflects the beat between the incoming RF-and LO-signals. Therefore, cooling must be fast and the heat capacity of the material must be low in order to achieve an as wide as possible IF-bandwidth. By the nature of the cooling process, we distinguish between diffusion-cooled and phonon-cooled HEBs. Theoretically, the noise performance of these devices should be independent of frequency and they are predicted to work well into the 10 THz regime, outperforming Schottky diode mixers.

While our understanding of the details of this type of heterodyne detector is still in early days, several groups in Europe and in the US are currently investigating HEB mixers and very encouraging results have been reported up to a highest operating frequency of 2.5 THz. The groups collaborating in the GREAT consortium are participating at the forefront of this technology. To share the technological risk we have agreed to focus on different, but complementary technological approaches.

4.1 Waveguide mixers with Nb microbridges

KOSMA will be responsible for the lower frequency channel of GREAT (1.6-1.9 THz). The group concentrates on the development of waveguide mixers using diffusion cooled (niobium) HEBs. The fast cooling required for high IF frequencies can be achieved with Nb microbridges that are small enough that hot electrons diffuse out of the bridge on a very short time scale and deposit their energy in a normal conducting (gold) heat sink. In order to make the devices small enough, the bridge dimensions need to be well below one micron, which can only be produced by electron beam lithography. Fig.4 shows an SEM micrograph of one of the first HEBs built in KOSMA's microstructure lab. These devices have been tested successfully at submillimeter frequencies. Currently new devices for frequencies beyond 1 THz are being manufactured.

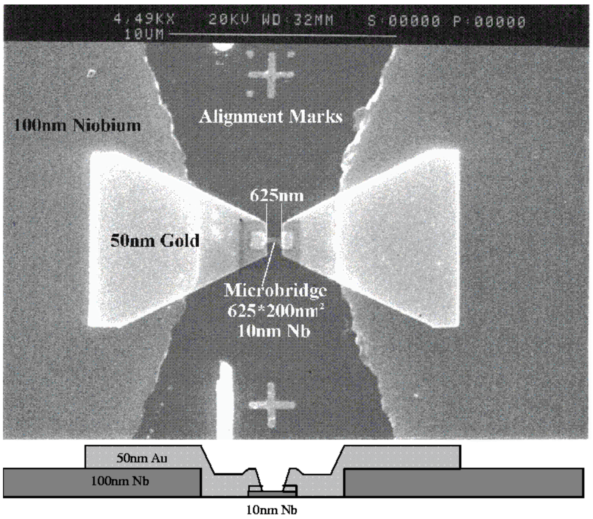


Figure 4. Diffusion cooled hot electron bolometer fabricated at KOSMA. In the niobium mircrobridge the electron bath is heated above the lattice energy level, cooling is by diffusion of hot electrons into the 50 nm gold pads.

On somewhat longer time scales there may be an even more promising alternative to niobium HEBs. Material data for aluminum indicate that it may be possible to build even more sensitive HEBs with even wider IF bandwidth out of this material. Since Al requires cooling down to 1.2 K in order to become superconductive, Aluminum HEBs are unlikely to be the detectors for the first flight series, but in the design of GREAT provision for dilution fridges has been made, which will offer a future upgrade of the instrument. For diffusion cooled HEBs we intend to use the waveguide mixer block design that has been very successful over the last years in receivers at the KOSMA telescope and elsewhere. At the higher frequencies, however, manufacturing the waveguide blocks and feedhorns becomes increasingly difficult. We are investigating techniques, including micromachining processes, that allow the fabrication these small mechanical structures.

4.2 Open-structure mixers with NbN mircobridges

Both, the DLR – in collaboration with the State Pedagogical University, Moscow – and the MPIfR, in close collaboration with IRAM, study the performance of niobium-nitride films, which due to their fast electron-phonon interaction can be used as phonon-cooled bolometers. Good progress has been reported by our DLR-partner at this meeting[2], using logarithmic-spiral antennas for coupling of the signal and L.O. reference to the HEB device. The active device in the open-structure mixerblocks at MPIfR, since a couple of years, is integrated with a planar (double-slot) antenna on an extended hyperhemispherical lens. This configuration has been optimized in detailed theoretical analysis in collaboration with Prof. Hansen from the Universität zu Wuppertal. A mixer of this type, hosting a SIS junction for operation in the 800-900 GHz atmospheric window, has successfully been used for astronomical observations at the Heinrich-Hertz-Telescope in winter 97/98[7].

5. BACK-END SPECTROMETERS

We have argued before that for many astronomical questions only high-resolution spectroscopy can provide the critical information about line shape and velocity structure that is badly needed for an understanding of the underlying physics. However, the wide range of astronomical topics, and hence requirements on spectral bandwidth and resolution, to be addressed with SOFIA is difficult to cover by one class of backend. For SOFIA we will have a choice of backends, with some flexibility in observing modes. With our US-partners interested in heterodyne research aboard SOFIA (J. Zmuidzinas, & A. Harris, responsible for the development of CASIMIR[6]) we have agreed on a common IF-interface and collaborative use of the backends.

5.1 The Acousto-Optical Spectrometer (AOS)[4]

Wideband AOS have become a standard tool in radioastronomy for spectroscopic observations in the mm/submm frequency range. Many observatories like e.g. AST/RO, KOSMA, CSO, HHT or SEST have been using such spectrometers exclusively for several years. Because of the relatively simple design of an AOS it is a very suitable instrument for airborne applications. Recent developments of AOS´s for SWAS with 1.4 and ODIN with 1 GHz bandwidth have demonstrated that this technology is also mature enough for space applications. This includes applications in radioastronomy, as well as in atmospheric planetary research for example. For SOFIA the maximum requested instantaneous frequency coverage in the GREAT instrument is 4 GHz in total, the frequency resolution should be about 1 MHz. This means that approximately 8,000 frequency pixels for full Nyquist sampling are required, which presently can only be provided at reasonable effort by AOS´s.
The maximum bandwidth of acousto-optical deflectors is limited due to the rather strong acoustic attenuation in the crystal materials at higher frequencies. This presently limits the maximum usable frequency, which can be efficiently processed in a Bragg-cell to about 3 GHz, if a resolution of 1 MHz is assumed. Therefore, 1.5 GHz (one octave) is approximately the maximum bandwidth of an AOS at higher frequency resolution. If a larger IF bandwidth needs to be processed, a hybrid solution is the only choice. The GREAT instrument is planned for up to 4 GHz IF bandwidth, therefore 4 times 1 GHz can be used for full frequency coverage. The concept of 4 individual AOS bands also allows operating 4 mixers (1 GHz bandwidth each) simultaneously.

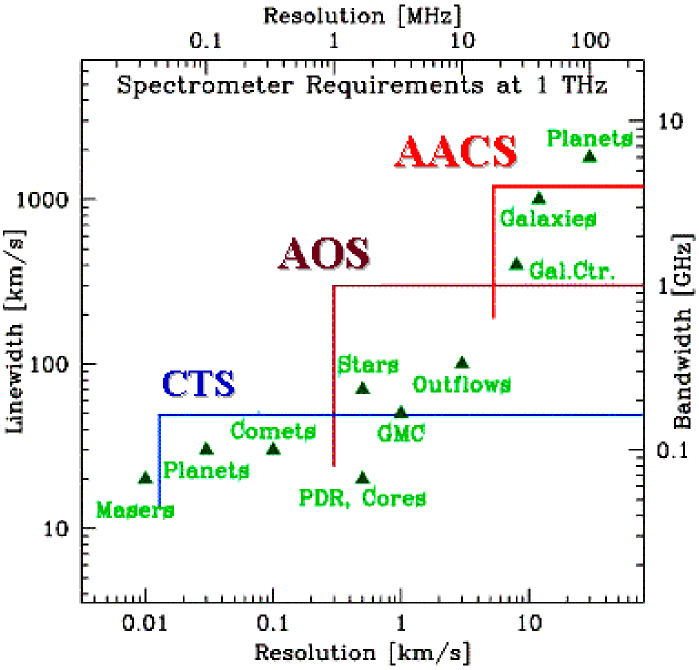


Figure 5: Astronomical requirements on spectral resolution and bandwidth (courtesy by A. Harris). Colored lines indicate the specifications of spectrometers under construction for SOFIA. The four-element AOS-array and the Chirp transform spectrometer are part of GREAT, the wideband analog autocorrelator (AACS) is under construction by A. Harris within the US SOFIA instrument program (CASIMIR[6]).

6.2 The High-Resolution Chirp Transform Spectrometer (CTS)

The principal of a chirp transform spectrometer is based on the Chirp Transform Algorithm, which is equivalent to the Fourier Transform. A space-qualified CTS has been developed by the MPI Aeronomie for the ROSETTA-MIRO mission[9]. For SOFIA´s first flights, MPI Ae will deliver one high-resolution module with 180 MHz bandwidth and 4096 channels (45 kHz spectral resolution), with the perspective of a later upgrade to an array with 5x180 MHz coverage.

6.3 The Wideband Analog Autocorrelator Spectrometer (AACS)

As part of the CASIMIR facility instrument, J. Zmuidzinas (CalTech) & A. Harris (U.Maryland) will develop an analog autocorrelator spectrometer for wideband, but lower resolution observations. The design will extend on the developments for WASP[5], a prototype that has been used successfully for astronomical observations at the CSO. The project goal is to provide 4 modules, 4 GHz wide with 250 channels each (spectral resolution: 16 MHz).

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