Compact 1.6-1.9 THz local oscillator as stand-alone unit for GREAT

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ABSTRACT

The German Receiver for Astronomy at Terahertz Frequencies (GREAT) is a first generation PI instrument for the Stratospheric Observatory For Infrared Astronomy (SOFIA), developed by a collaboration between the MPIfR[1], KOSMA[2], DLR[3] and the MPAe[4]. GREAT is designed as a dual-channel, tri-band receiver, covering the frequencies of 1.6-1.9 THz, 2.4-2.7 THz and 4.7 THz . Each of the first three institutes named above contribute one heterodyne receiver channel, respectively. A later upgrade with an e.g. 1.4 THz channel will follow.

The GREAT instrument is designed to observe with any two of the three frequency channels simultaneously and to be able to quickly switch between different flight configurations. This demands a high modularity and flexibility on our receiver concept. For this purpose, we must be able to exchange the cryostats containing the mixer devices, the optical benches and the local oscillator subsystems (LO). Especially the LO systems are built as stand-alone units and integrated into compact boxes. KOSMA contributes GREATs heterodyne receiver channel operating at a frequency of 1.6-1.9 THz. We present an overview of the 1.6-1.9 THz LO system, and a detailed description of its internal parts.

Radiation of 1.9 THz is generated by means of a Backward Wave Oscillator (BWO) followed by a frequency tripler. The estimated output power at 1900 GHz is about 1μW. To correct the BWO's considerable elliptical output beam pattern we developed astigmatic off-axis mirrors to achieve maximum beam coupling into the tripler's feed horn antenna. All mirrors are manufactured in-house on a 5 axis CNC milling machine at KOSMA. To phase-lock the BWO we use a custom-made two-stage PLL system with a Gunn oscillator as intermediate LO. The PLL system is located in a small compartment in the front of the LO-box. Schottky mixers for 633 GHz have been manufactured at KOSMA. The required magnetic field of about 1.25 Tesla for the BWO-tube is provided by a permanent magnet. This solution makes the oscillator independent from high current electromagnets as well as helium infrastructure for superconducting magnets. The BWO-tube produces approximately 150 Watt of excess heat. We integrated a high efficiency chiller into the LO-box designed to dispose of this heat with a minimum additional power consumption and space requirement. The complete LO-system fits into a small box with 21cm x 24cm x 100cm in size and consumes only 230 Watts of power.

1. SCIENTIFIC BACKGROUND

Improving THz astronomy will complete our knowledge about planetary atmospheres and the interstellar medium in the galaxy. Furthermore, investigations related to the early universe will be possible. THz observations are expedient at places only where the atmospheric transmission of the spectral range is high and not blocked due to water vapor absorption. Thus, excellent sites for THz observations have to be extremely dry like space applications or in our case we will use the Stratospheric Observatory For Infrared Astronomy (SOFIA) operating at an altitude of about 13km.

The GREAT receiver attacks the long standing gap in the far infrared spectral range up to 4.7 THz. The KOSMA 1.9 THz detector will provide information about the atomic fine-structure transition of ionised carbon CII

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(158 μm) which is the most important cooling line of the interstellar medium. In addition, C+ is found to be abundant in photo-dissociated regions (PDR), where FUV photons from the interstellar radiation field and/or emitted from young stars dissociates molecules such as CO and ionize carbon. Thus, the 1.9 THz receiver channel in conjunction with the 4.7 THz channel of the DLR (64 μm, fine-structure line of neutral atomic oxygen OI) makes it possible to verify our recent models on PDRs.

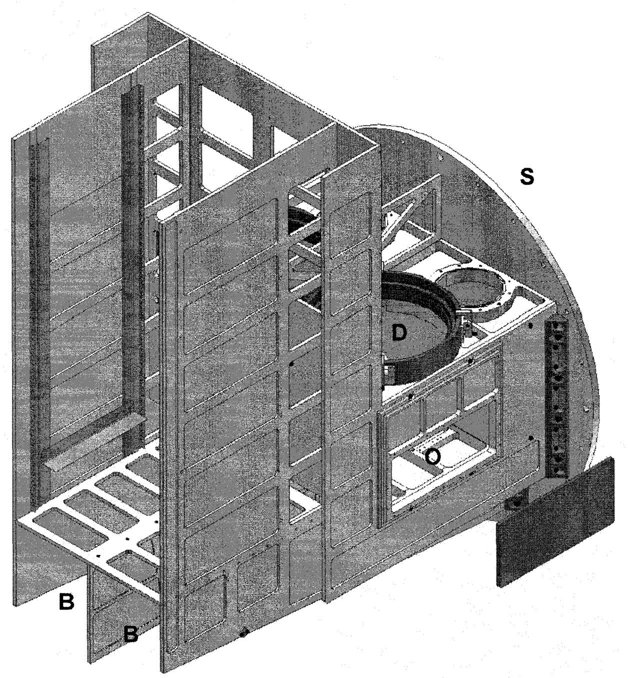

Figure 1: The GREAT structure: (S) SOFIA instrument flange; (O) common optics plate, (D) dewar mounting for cold optics and mixer; (B) local oscillator slots

2. GREAT RECEIVER CONCEPT

GREAT is a single pixel heterodyne receiver carrying two independent receiver channels at once. A total of three receiver channels, contributed by the MPIfR, KOSMA and the DLR are available (1.6-1.9 THz, 2.4-2.7 THz and 4.7 THz). Depending on the scientific purpose of a mission, two channels are selected and will be in operation simultaneously. This requires a high degree of modularity for the receiver system and for the common optics needed. To ensure the interchangeability, each channel contains its own exchangeable local oscillator box, a specific optical bench mounted on the common receiver optics and a cryostat containing the mixer device. When swapping receiver channels, all three subcomponents have to be replaced. Each receiver channel can operate in either receiver slot.

Pumping all three receiver channels with only one type of LO is not possible at present. At GREAT we will use three completely different types of local oscillators. A standard solid-state LO provides 2.4-2.7 THz. The upper band of 4.7 THz is covered by an OPFIRL and radiation at 1.6-1.9 THz is generated by a Backward Wave Oscillator (BWO) followed by a frequency tripler. To make these three systems interchangeable, they were designed to fit in small boxes with 21cm x 24cm x 100cm in size located at the bottom of the GREAT structure (see Figure 1). Each LO-box has to contain the whole LO-subsystem including the control electronics to work as an independent and exchangeable THz source. The boxes are inserted into the LO-slots, clamped and automatically aligned precisely to guarantee a reproducible coupling of the THz beam into the common optics. Interchangeability of the receiver channels results in additional requirements to the mechanical setup but it opens up the possibility to upgrade them easily to the newest technology by modifying either the LO subsystem, the corresponding optics bench or the mixer inside the cryostat as well as adding completely new receiver channels.

3. THE 1.9 THZ LOCAL OSCILLATOR SETUP

The detection frequency of the KOSMA receiver channel will be in the range of 1.6-1.9 THz (158-188 micron). This wavelength is a serious gap for the design of local oscillator sources with sufficient output power even to pump a single mixer device (about 1μW). Solid state LOs attack this gap from the lower frequency side. LOs based on mixing two IR-lasers are well under development. Using a laser LO is not possible for our application due to the insufficient tuning range of such a laser. Quantum cascade lasers (as we may use in the SOFIA Terahertz Array Receiver: STAR) developed for this frequency range require superconducting magnets and liquid helium cooling, which is not easy to accommodate in the modular LO-box of GREAT.

In our case radiation of 1.9 THz is generated at 633 GHz with a Backward Wave Oscillator (ISTOK, Russia, model No. OB-80) followed by a frequency tripler. Figure 2 shows the general setup. The BWO-tube is mounted inside a cylindrical permanent magnet (1.25 Tesla) to focus the electron beam for oscillation. The 633 GHz beam leaves the BWO output horn, passes an astigmatic optics and is coupled into the tripler's feed horn antenna (see section 4, Optics Design). The tripled 1.9 THz beam is then focused by an off-axis mirror and leaves the LO-box through a hole in the back of the top lid. A small fraction of the 633 GHz beam is coupled out by a beam splitter and fed into a PLL system to stabilize the BWO frequency (see section 5).

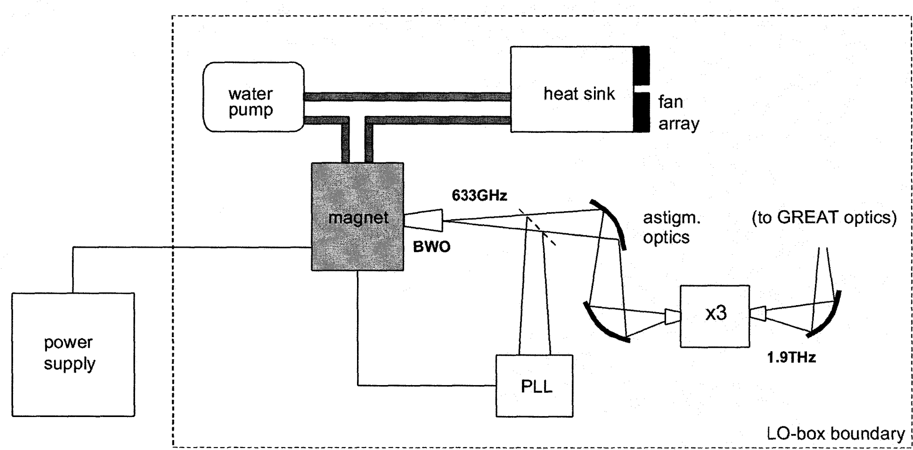

Figure 2: The local oscillator setup

An external high voltage supply (HVS) provides the cathode heating current (6ACV, 1A) as well as the acceleration voltage necessary for the BWO-tube (4000V). Since the acceleration voltage directly determinates the frequency of the BWO output beam, it has to be very clean and is filtered to a voltage ripple of <10mV. The cathode current is about 30mA at 4000V. In addition to the heating power of about 8 Watts the BWO-tube dissipates 130 Watt. For this reason water cooling is required. We implemented a custom-made chiller into the LO-box to dump this excess heat with a power consumption of only 50 Watts and a minimum space requirement. It consists of a fan array, a specially manufactured heat sink and a small aquarium water pump. The air is taken into the LO-box at the bottom and blown out through a slit in the front plate. Using this subassembly we are completely autonomous from external commercial chillers with a typical power consumption of 2000 Watt and the burden of additional safety regulations on SOFIA. A typical flight air pressure of 750mbar and a BWO excess heat of 130 Watt leads to a water heating of only 5K. The interconnection between high voltage, water and the IF-processing as well as phase lock and control electronics require additional safety systems all integrated in the LO-box and discussed in section 6.

4. OPTICS DESIGN

Radiation of 1.9 THz is generated by means of a Backward Wave Oscillator (BWO) followed by a frequency tripler. The output power of the BWO is between 5-20 mW at 633 GHz. The output beam pattern is considerably elliptic with different beam waists in horizontal and vertical direction. The fraction of power in the fundamental Gaussian beam mode is about 89.9%. To achieve maximum beam coupling into the tripler's feed horn antenna we developed astigmatic off-axis mirrors manufactured in-house at KOSMA.

An astigmatic off-axis mirror is defined by three phase centres resulting in two different focal lengths for the ellipsoidal and spherical direction. If the positions and even the horizontal and vertical waists w_{0x} and w_{0y} of the beam are exactly known, the radii of curvature (R) at an arbitrary plane can be computed. Via the law for small lenses, in Gaussian optics valid for R, the focal lengths of adequate off-axis mirrors can be calculated to reimage the waists at a given distance z.

Numerical simulation show excellent imaging properties of our astigmatic optics. First results of the *measured* corrected BWO beam profile demonstrate an increase in gaussicity up to 98.9% in comparison to only 89.9% in the uncorrected beam (see Figure 3). This illustrates that astigmatic optics can be calculated and manufactured with high precision and could be also useful for more severe elliptic beams from sources such as quantum cascade lasers as we intend to use in the SOFIA THz Array Receiver (STAR) from KOSMA.

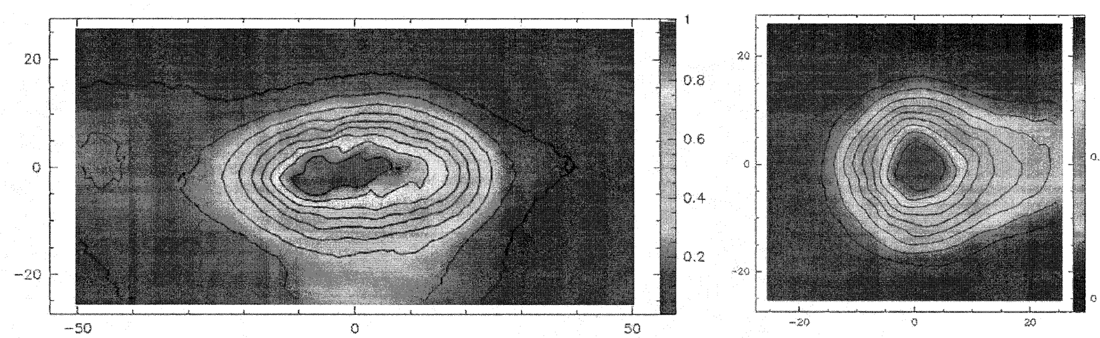

Figure 3: Measured BWO beam pattern at a distance of 335mm from the output feed horn (left). The right hand picture shows the corrected beam. Note, that our first measurements are based on a rude and visual aligned $4w_0$ mirror optics only which can explain deviation of a perfect Gaussian beam profile in conjunction with the distorted BWO input beam pattern.

The corrected 633GHz beam is then coupled into the tripler's feed horn antenna, a potter horn with a centre frequency of 600GHz. The tripler itself will be based on a coaxial design made by Radiometer Physics GmbH, Germany, with an estimated output power of about 1μW at 1900 GHz. The output beam is focused by an off-axis mirror, leaves the LO-box through a hole in the top lid and enters the common optics plate of GREAT from the bottom. A 2mm thin high density poly ethylene window inside the GREAT structure separates the inner compartment of GREAT from the LO-box, since the common optics is at outside air pressure whereas the LO-boxes are at cabin pressure. To guarantee correct beam coupling into the common optics, the last mirror inside the LO-box is adjustable. After switching a channel, adjustments can be made even during flight if the SOFIA telescope is caged. The complete optics is located at the back side of the LO-box and vertically orientated, for minimum space requirement.

5. PHASE LOCK ELECTRONICS

The BWO has an inherent 3dB line width of less than 1kHz. However, fluctuations of the supply voltage directly affect the BWO frequency and broaden the signal to ~20MHz. To avoid this, one has to control the 4000V cathode voltage with a maximum noise of 10μV over a cable distance of 25 meter (BWO to HV-supply). As a solution we implemented a PLL system into the LO-box (Figure 4). Instead of controlling the high voltage, frequency regulation is achieved by shifting the BWO's *ground* potential. In this way, the PLL system can be placed very close to the BWO to obtain best performance. The result is shown in Figure 5. We achieved a SNR of 50dBc for Δf=10kHz. Even for the frequency tripled 1900 GHz beam, this is enough to benefit from the full resolution of the chirp transform spectrometers (CTS) on GREAT (Δf=45 kHz).

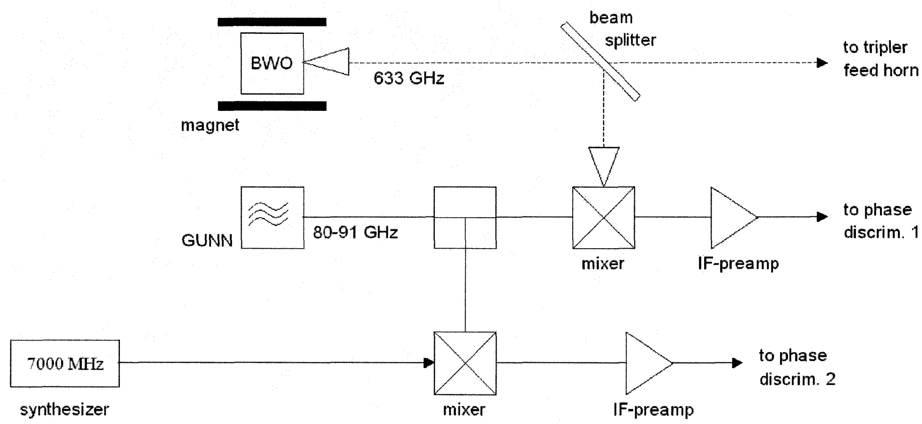

Figure 4: The setup of the dual-PLL system. For explanation see text.

We use a Gunn oscillator as stable reference for the PLL loop. A small fraction of the BWO beam is coupled out via a beam splitter and feed into a harmonic mixer. The signal is combined with the 7th harmonic of the Gunn and forms the IF-signal for the PLL. The complete IF processing chain is integrated on the PLL card and designed to be extremely low-noise (0.9 dB). To function as a stable reference, the Gunn oscillator is stabilized by a second PLL circuit, which uses the 13th harmonic of a high precision frequency synthesizer as the Gunn reference oscillator.

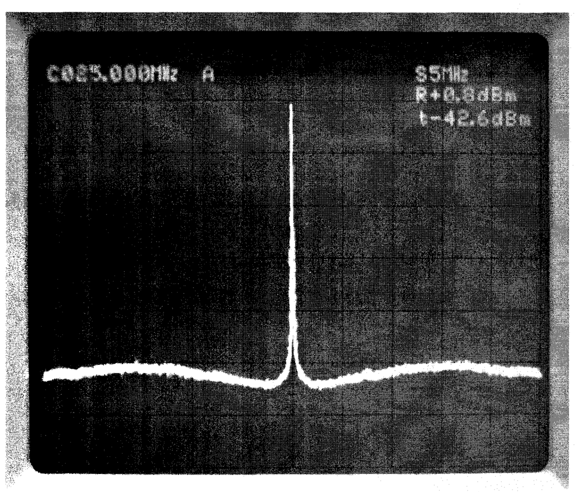

Figure5: The measured BWO IF-Signal.

Temperature fluctuations affect the Gunn frequency with about 1MHz/K and may result in loosing the lock of the PLL. We effectively increased the holding circuit range with an additional feed-back loop. The correction signal of the PLL is monitored and used to control the main Gunn voltage within a range of 7-10 volt, corresponding to a frequency drift of 1.5 GHz. Doing this the Gunn PLL appears to be ultra stable against long time temperature variations and can not loose the lock in any case.

6. SAFETY CONSIDERATIONS

The interconnection between high voltage, water and sensitive electronics inside the LO-box leads to the possibility of many different kinds of hazards. This becomes a serious problem, since the SOFIA airplane is built to be a science platform and to carry additional *civil* passengers for education and scientific motivation. For this reason, all science instruments on SOFIA have to meet the whole spectrum of safety regulations for airworthiness certification of the FAA (Federal Aviation Administration). We implemented several systems to guarantee a safe operation of the LO-box:

The high voltage supply (HVS) of the BWO contains an emergency circuit (*crow bar*) which is controlled by measuring the output current of the HVS. In case of a short circuit, the supply current will increase exceeding a fixed predetermined value. As a result, the high voltage will be switched off and the output capacitors of the HVS will be discharged within 50μs. The small shut-down time protects the electronics as well as crew members by limiting the discharge energy to a maximum of 0.5 Joule.

There is the possibility that an arc discharge develops inside the BWO-tube. In this case, its internal resistance drops to below one Ohm and the high voltage of 4000 Volt would be directly applied to the PLL output circuit. Although this is limited by the crow bar, the electric surge would be enough to damage the PLL and following electronics. To avoid this, we implemented a "protection circuit", placed between the BWO and the PLL. If the voltage at the PLL output rises above 15 Volt, the current will be dumped into large capacitors. Thus, the voltage will be kept below 20 Volt at all times causing no harm to the electronics.

The fast emergency switch-off circuit can be externally triggered, too. Various sensors measure e.g. the water flux and the water temperature of the chiller. If the water circuit is interrupted or the water temperature exceeds a maximum value for sufficiently cooling the BWO, the electronics will send a trigger pulse to the HVS to deactivate the high voltage to prevent overheating of the tube.

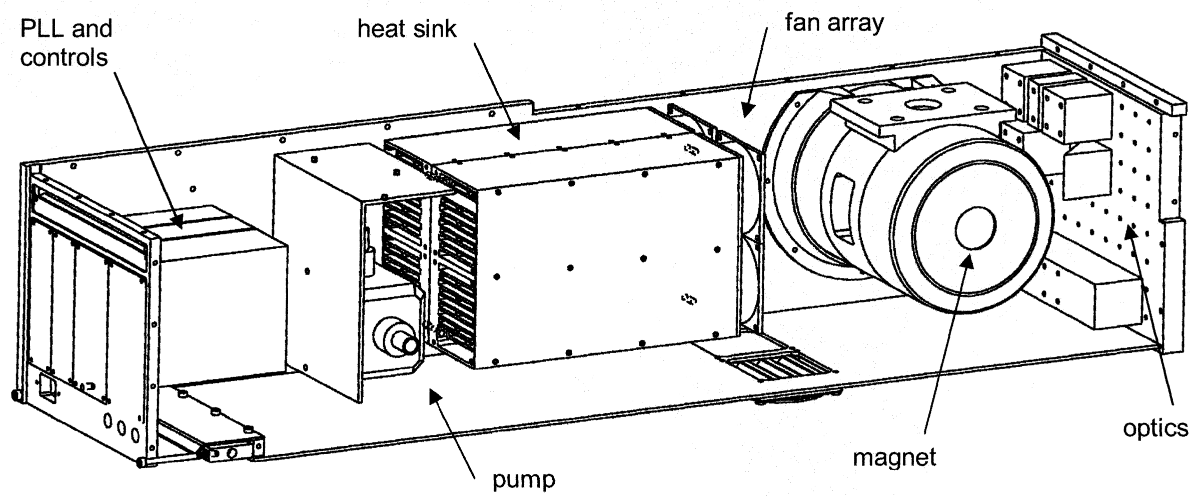

Figure6: Chart of the assembled LO-Box

7. CONCLUSION

We described the 1.6-1.9THz local oscillator for the GREAT receiver. The system is designed to be an exchangeable plug-in device and fits in a box with 21 x 24 x 100cm in size. It contains no helium infrastructure and needs no external chiller. The system power consumption is only 230 Watt and the estimated output power will be 1μW at 1900 GHz. We meet the SOFIA airworthiness safety regulations. A schematic of the assembled LO-box is shown in Figure 6.
We developed a theory of astigmatic off-axes mirrors to correct the BWO output beam pattern.

ACKNOWLEDGMENTS

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