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# The High Resolution Spectrometer for SOFIA

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## Abstract

The high sensitivity provided by SOFIA (Stratospheric Observatory For Infrared Astronomy) and the spectral resolution obtained with the CTS (Chirp Transform Spectrometer) combine in a unique tool in order to address a wide range of topics of modern astrophysics, from questions about comets, planetary atmospheres and the interstellar medium in the galaxy to investigations related to the early Universe. Thanks to high resolution spectroscopy we can obtain atmospheric information from the shape of a spectral line, and with this retrieve the altitude distribution of molecular species, for instance water vapor on Mars and HCl on Venus. Most of the cometary radiation is in the infrared range, as their equilibrium temperature is rather low. But since most of this radiation is absorbed in our atmosphere, an observatory located at 12 Km will improve our spectroscopic capabilities in cometary bodies. These scientific demands represent also new scientific challenges in the spectrometers and receivers field. The use of digital technologies to simulate a matched expanded chirp signal and the mathematical modeling of electrical devices, allows us to achieve high resolution and dynamic range.

## SOFIA Observatory

The strong IR absorption of our atmosphere encouraged the development of SOFIA, a flying observatory, mounted onboard a Boeing 747SP, that will open in 2004 a new era in the MIR (Medium InfraRed) and FIR (Far InfraRed) astronomy. The infrared radiation is strongly affected by absorption of molecules like water vapor and $CO_2$, specially the range between 30µm and 1mm that is inaccessible from ground, even from observatories located at high altitudes as the Manua Kea in Hawai. SOFIA contains advantages of ground based observatories as high reusability, easy maintenance and the capability to avoid the first 12 Km of atmospheric absorption (85% of the earth atmosphere and 99% of the water vapor).

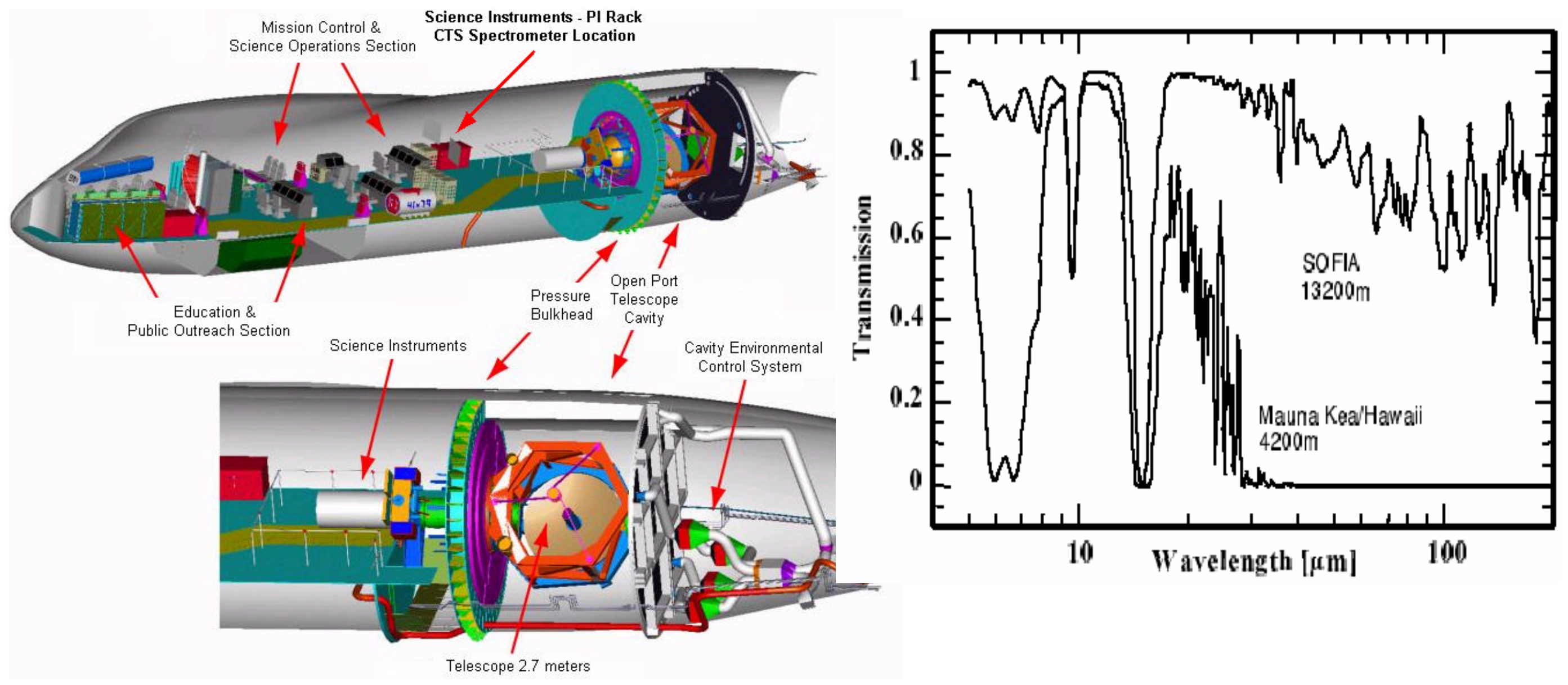

Fig. 1: (a) A view of the planned interior of SOFIA observatory. (b) Comparison of the atmospheric transmission between the Mauna Kea observatory, one of the best infrared sites on ground, and with SOFIA.

The Cassegrain-type telescope will collect radiation from a wide spectral range, 300 nm to 1 mm (1000 THz to 300 GHz), with a main dish of an effective diameter of 2.5 m, allowing spatial resolutions of 1 arc-sec. GREAT (German REceiver for Astronomy at Terahertz frequencies) with CTS will provide SOFIA of high resolution spectroscopy by a coherent detection of the incoming radiation. GREAT will cover three IR bands: a low frequency band of 1.6-1.9 THz (188 - 158 µm), a mid frequency detector centered at 2.6 THz (115 µm) and a high frequency channel at 5 THz (60 µm).

## CTS Spectrometer

The Chirp Transform Spectrometer is based on the velocity dispersion of sonic surface waves, which is controlled by micro-structures on the surfaces of defined crystals. These dispersion properties allow us to perform a real-time convolution. The time-frequency transformation is performed by a correct combination of the dispersion features of two SAW (Surface Acoustic Wave) filters, an expander and a compressor. One critical parameter is the matching between the SAW filters, the resolution and the dynamic range depends strongly on this parameter, that can optimized by using a digital phase accumulator to produce an expanded chirp waveform.

## Chirp Transformation

The Chirp Transformation is a time-frequency domain transformation, the principle behind the CTS spectrometer. This can be derived from the Fourier Transform equation,

$$F(w) = \int_{-\infty}^{+\infty} f(t)e^{-jwt}\,dt$$

and substitute ? = 2pµt we have

$$F(2\pi\mu\tau) = \int_{-\infty}^{+\infty} f(t)e^{-j2\pi\mu\tau}\,dt$$

Using the identity 2tt = $t^2 + t^2 - (t - t)^2$ this becomes the

$$F(2\pi\mu\tau) = e^{-j\pi\mu\tau^2}\int_{-\infty}^{+\infty}\left(f(t)e^{-j\pi\mu t^2}\right)e^{j2\pi\mu(\tau-t)^2}\,dt$$

so called chirp transform. This can be interpreted as the input signal is mixed (i.e. multiplied) to a chirp waveform (e-jpµ$t^2$) so that each Fourier component is converted into a chirp located in the frequency according to the component's frequency and in the time domain according to the dispersion function of the acoustic filter. The mixed output is processed in the compressor chirp filter of matched slope which correlates, or pulse-compresses, the constituent chirps.

## New developments

Several new developments have been done on different aspects of the spectrometer.

- As expander is used a digital chirp waveform generated by a quadrature phase digital synthesizer. The main advantages of using this modern digital technologies is the low-cost, optimum adaptation of the quadratic phase response of the compressor filter and high dynamic range.
- The realization of frequency filters at GHz frequencies was possible thanks to an intensive study of the electromagnetic field distribution over quasi-dielectric thin mediums (microstrip).
- Mathematic modeling and numerical simulations of the different RF components were important to estimate and optimize the performance of the complete spectrometer.

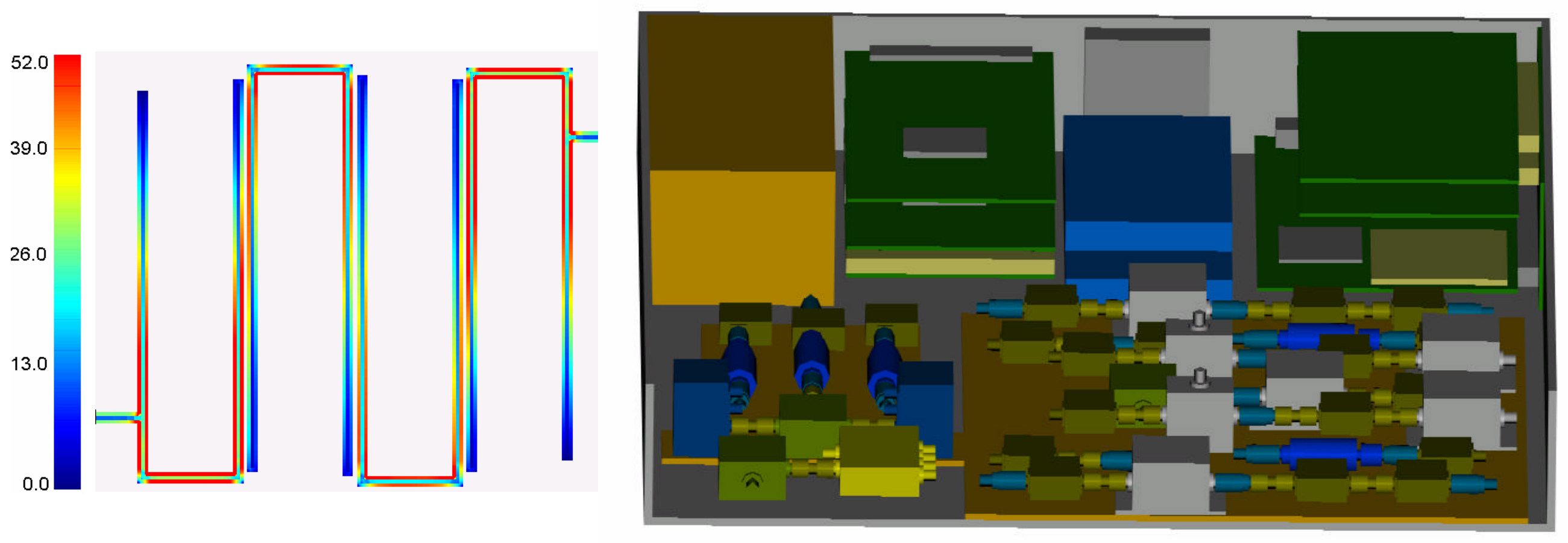

Fig. 2: (a) Simulation of the surface currents of a resonant mode in the hairpin filter type. Scale in amperes. (b) 3D View of the SOFIA-GREAT-CTS expected interior.

## Preliminary results

The demanded high frequencies were achieved by digital generation, quadrature modulation and frequency multiplication. By the development of RF models and laboratory experiments, it is seen that the non-linear properties of an analog amplifier can be used as frequency multiplier. The simulation of matching features between the digital phase accumulator and the SAW filter (including spurious contribution) were confirmed by several measurements, leading us to estimate high dynamic range and high resolution.

Expected CTS specifications:

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|---|---|
| Bandwidth: | 204.8 [MHz] |
| Spectral resolution: | 50 [KHz], 4096 points |
| Spectral density: | -44 [dBm/MHz] |
| Dynamic range | 40 [dB] |

## Outlook

The joint between modeling, simulations and development of several technologies allow us to achieve the high scientific demands expected from the SOFIA observatory. This performance will let us address topics such as the distribution of atmospheric compounds on planets and comets. Based on a photochemical model of the Martian atmosphere (Nair et al. 1994), we can estimate how the spectra of the 1.893 THz (158.3 µm) rotational transition would be measured with the CTS.

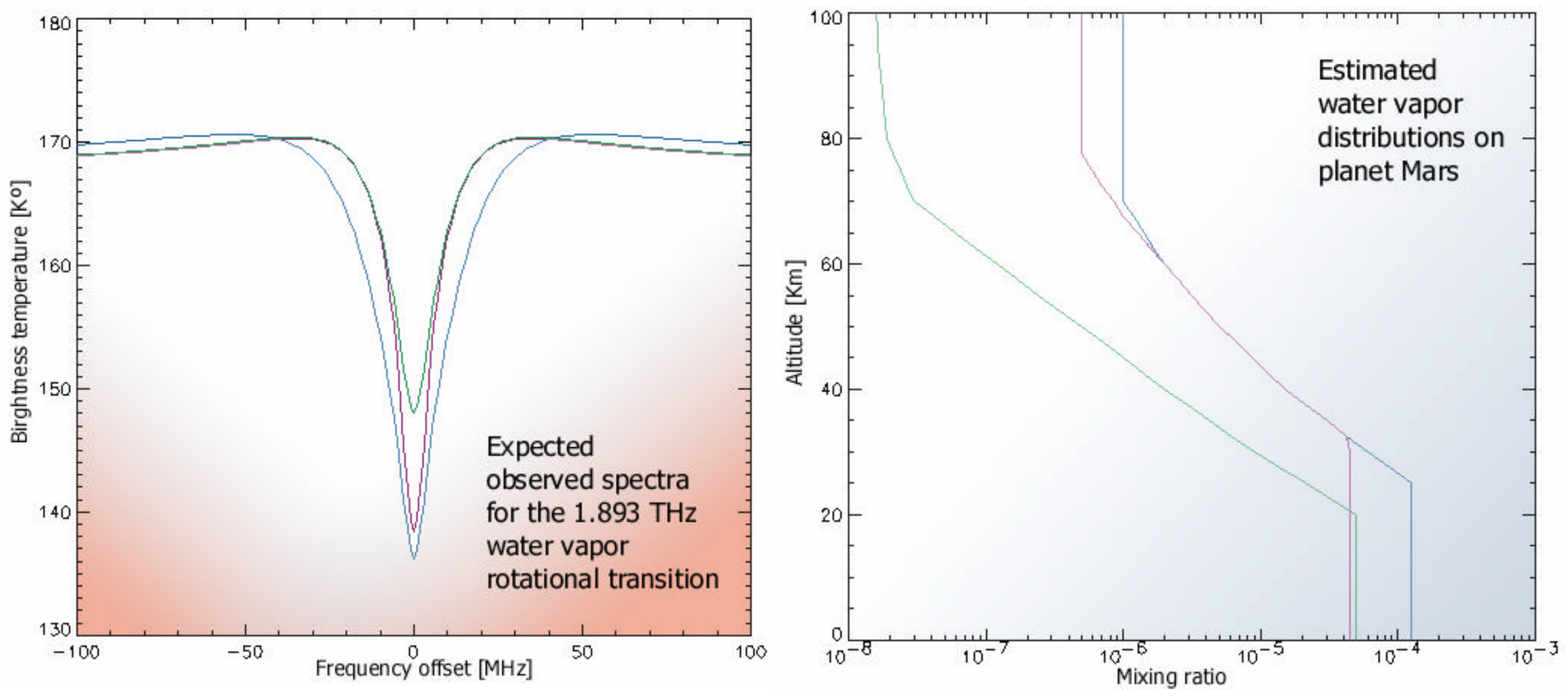

Fig. 3: (a) Simulated spectral lines for the rotational transition of the water vapor molecule, based on a modeled Martian atmosphere. (b) Possible retrieved profiles of water vapor on the red planet.

## References

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