Terahertz Radiometer for Outer Planet and Moon Atmospheres (TROPA)

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***Abstract* —We are developing a prototype instrument platform to demonstrate the feasibility of a wideband spectrometer for planetary applications under a three-year NASA research program. This development focuses on three specific areas needing advancement. First, the terahertz portion consists of an optical bench with dual heterodyne Schottky-mixer based receivers, one for each band. The beams entering the horns of the two receivers are de-multiplexed from the input beam by a polarizing beam splitter. The blocks containing the 560 and 1200 GHz mixer are more highly integrated than previous space instruments to reduce mass and volume. The receivers take a fundamental pump frequency near 30 GHz and multiply up to the submillimeter range.**

Second, a rapid-tuning, low-phase noise, and low-power 33 GHz range LO synthesizer is being prototyped. The low phase noise requirement is needed because of the factor of 36 multiplication to reach 1200 GHz, giving a requirement that the integrated phase noise from 100 kHz up be less than 0.6 degrees. The synthesizer will require about 6 watts.

Finally, we are developing an advanced polyphase filter back-end spectrum analyzer with a bandwidth of 750 MHz, and power consumption of about 3 Watts and 4096 channels. This system is based on a simple three-chip architecture, having a commercial 1.5 GS/s analog-to-digital converter, an ASIC to do the filtering and an advanced FPGA for data processing and control.

I. Introduction.

For several years now, ESA and NASA have turned their attention to an Outer Planet Flagship Mission (OPFM) to the Jupiter system (focusing on Ganymede, Europa and other Galilean moons, as well as Jupiter itself [1]) and to the Saturn system (focusing on Titan [2]). Both studies call for inclusion of a submillimeter/Terahertz instrument to perform a new category of measurement. More recently, the mission has been accepted for funding as an ESA L-class mission[3]. The Jupiter measurements will greatly expand on those from the Juno mission currently being built. The prime target will be Jupiter's stratosphere, which links the deeper troposphere whose dynamics are dominated by Jupiter's internal energy sources with the upper atmosphere that interacts strongly with the space environment. In the lower atmosphere small-scale convection control the dynamics, but these generate the larger scale waves that travel up from the cloud levels to the stratosphere, where they interact with larger scale flows. These processes are presently very poorly understood; improving the understanding of these dynamics is a key goal of the sub millimeter instrument.

We are reporting on a NASA-funded brassboard of the instrument known as the Terahertz Radiometer for Outer Planet and Moon Atmospheres (TROPA). The Terahertz spectrometer will

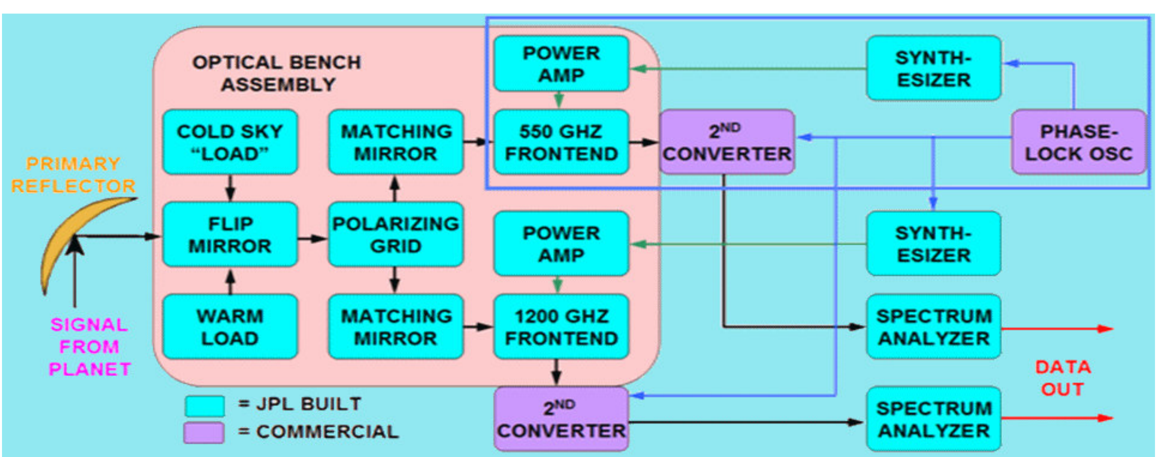


Fig. 1. Block diagram of TROPA, showing the optical bench, receiver front ends, synthesizers and back end spectrum analyzers.

complement microwave and IR instruments; it is the only technology capable of resolving winds, temperature, pressure and composition in this critical layer of the atmosphere, and will fill the gap left by the other measurement technologies. It operates in the submillimeter frequency range, with two receivers: one for 520 to 590 GHz, one for 1100 to 1300 GHz. See the block diagram in Figure 1. It has two features that differentiate it from previous space-borne radiometers in this frequency range: the wide tunability and rapid frequency switching (<20 ms). The receivers are based on Schottky diode mixers, developed at JPL, and have a sensitivity of about 2500 K at 550 GHz, 6000 K at 1200 GHz. The mixers are pumped by local oscillator (LO) sources also developed at JPL, and also based on cascaded chains of Schottky diode frequency multipliers to provide about 3 mW at 600 GHz. The mixers translate the input signals to an intermediate frequency (IF) that is analyzed in a new, low-power digital polyphase backend spectrum analyzer with 750 MHz bandwidth, 4096 channels, and consuming approximately 3 W. The sources for the LO multiplier chains is a pair of rapid-tuning, state of the art low power LO synthesizers, with output frequencies around 100 GHz, and consuming approximately five watts each. The total instrument should have a total power consumption of about 20 watts, and a mass of 10 kg.

II. Optical Bench Design.

The input signal from the planet will be received and concentrated by the primary telescope into the optical bench that splits the two frequencies and conveys the separated beams into the receiver front ends. The design started with a lower-frequency optical bench designed by one of the authors [4] for MIRO, a comet observation submillimeter-wave instrument at 190 and 564 GHz. The fundamental principle is that the frequency separation is not made by frequency dependent components, but rather by a polarizing beam splitter. The receivers for the two frequencies are cross-polarized. Since each receiver only accepts a single polarization in any case, no signal is lost that would not be lost even without the polarizer, and the loss is greatly reduced and the optics greatly simplified.

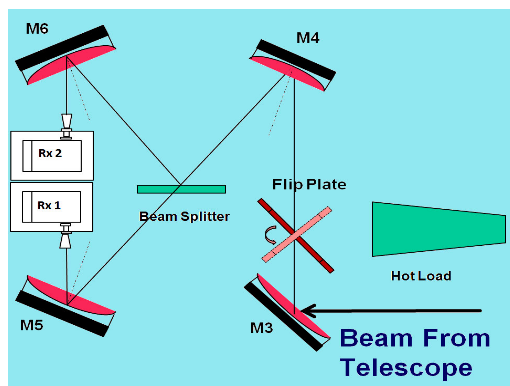


Fig. 2. TROPA optical bench schematic.

The scheme devised for TROPA is illustrated in Figure 2. The incident beam from the telescope is deflected from its input direction into the plane of the optical bench by mirror M3. It passes a flip mirror toward mirror M4. The flip mirror allows the beam incident on M4 to be selected between the calibration hot load and the beam from M3. M4 re-directs the beam toward the beam splitter. The splitter is aligned to pass the horizontally polarized signal toward M5 and the 1200 GHz receiver, Rx 1, and reflects the vertically polarized signal toward M6 and the 560 GHz receiver, Rx 2.

Designing the optical bench is an exercise in constrained optimization. The initial design uses a Gaussian beam methodology [5], where the beams between each optical element is described by the waist diameter, w_0, and location. The scientific requirements on the instrument dictate that the spot resolution at the planet be the diffraction limited for the given reflector diameter at each frequency. This implies that the main telescope be illuminated with the same taper for each frequency. Thus the Gaussian beam diameters in the far field of M3 should be the same. Since the far-field spreading half-angle, θ_S of a Gaussian beam is given by [5]

$$\theta_S \cong \frac{\lambda}{\pi w_0}, \quad (1)$$

for wavelength λ. Hence, the output beams of M3 must have their waist to wavelength ratio matched. Furthermore, for both frequencies the radii of curvature and beam radii must be

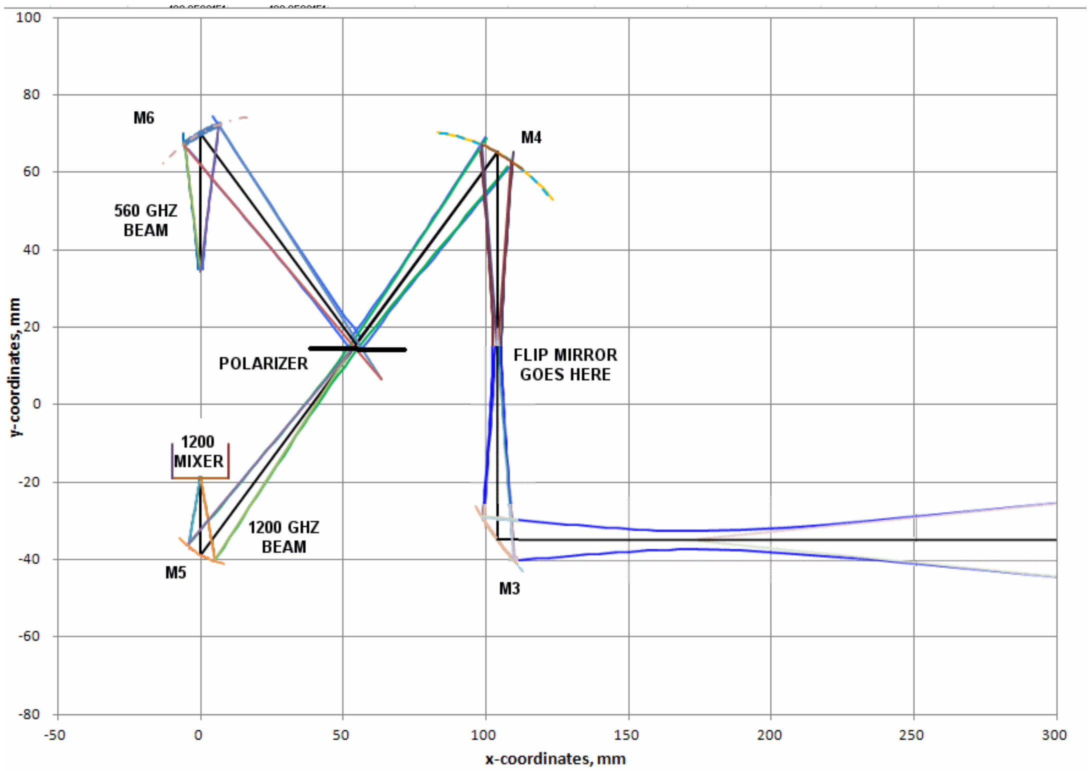


Fig. 3. TROPA optical bench spreadsheet design.

matched to the focus-to-ellipsoid distance of the reflectors. There are also the geometrical requirements for the position and sizes of the blocks, and the horn antennas of each frequency. The beams must not impinge on the blocks. Since the block sizes are similar to those in reference [4], this becomes more difficult at the higher frequencies, especially the 1200 GHz channel.

Finally, the beams are matched to the receiver horns by M5 and M6. The horn used for the 560 GHz band is a commercially procured corrugated scalar horn. The 1200 GHz horn is a diagonal design, machined directly into the block. In order to facilitate optimization of the design, a spreadsheet has been generated that directly plots the beam radii and foci. Figure 3 shows the plots of the current design. A Solidworks file has been produced that generates a solid model for the mirrors based on the parameters (semi-major and semi-minor axes) determined by the spreadsheet. Machining will begin shortly.

III. Front End Receivers.

560 GHz receiver. The 530 to 590 GHz mixer block incorporates two features that differentiate if from most [6]: **(A)** to be compatible with the TROPA optical bench design described above, the RF beam must enter at right angles to the LO waveguide. Most previous JPL mixer blocks have the RF and LO ports co-linear. **(B)** The second unusual feature is incorporation of a waveguide twist at the RF input. Almost all submillimeter waveguide blocks we use have the electric field parallel to the split between the two halves of the block, making the split in the E-plane rather than the H-plane. This is because a) it is easier to machine and b) lower loss than the alternative H-plane split, because the waveguide surface currents would then be required to flow across the split. However, in our optical bench scheme, one receiver must receive signals with E-field parallel to the bench plane, and one with the E-field normal to the bench plane. We decided to make the 560 receiver perpendicular, thus requiring a rotation of its input waveguide. (If the input and output guides were co-linear, the twist could be in the LO waveguide, but in the right-angle alignment we are using that would put the input in the top of the block.)

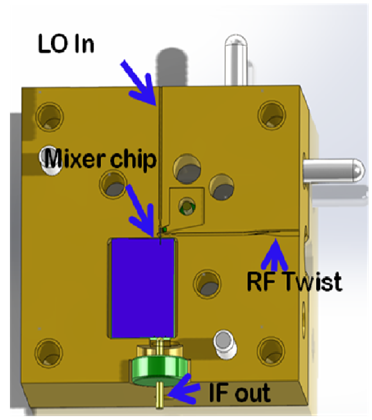


Fig. 4. New 560 GHz block with polarization twist.

The 560 GHz block is shown in Figure 4. It has been received but not assembled and tested yet; that will occur shortly.

1200 GHz mixer. We have measured the 1200 GHz mixer. This is the highest frequency we have ever measured for a subharmonically pumped mixer using JPLs planar process (In fact, all higher frequency mixers the authors are aware of, including other JPL fabricated mixers are fundamentally pumped). The receiver chain is shown in Figure 5 and an initial measurement is reported in the poster presented at this conference by B. Thomas [7]. The noise temperature is in the range of 4000 to 6000 K double sideband (DSB).

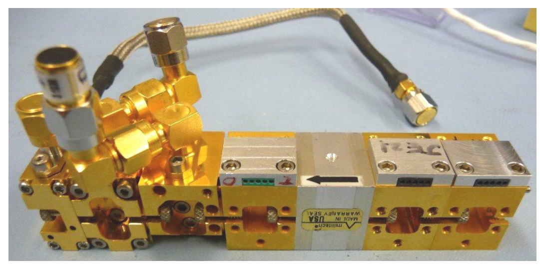


Fig. 5. 1200 GHz receiver: the mixer is at far left, with 600 GHz tripler and 200 GHz doubler next. Four right-most blocks are the amplifiers.

Compact 1200 GHz Blocks. We are in the process of designing a new pair of blocks for the 1200 GHz channel. One will include a new 570 to 650 GHz tripler that is intended to expand the frequency range of the receiver to higher frequencies, as mentioned above. This block also includes the right angle bend necessary for compatibility with the optical bench design. Using this design, several goals are accomplished: first, it allows us to implement a new concept with a dual-combined tripler/mixer block (see Figure 6). The two blocks fit together as if they were one, and take up the same 20×20×20 mm^3 space as a single block. This makes it possible to keep a collinear RF/LO design for the 1200 GHz mixer. The co-linear design has the advantage of shorter high-frequency waveguides, giving lower loss and better performance. The bend occurs in the 200 GHz waveguide input to the 600 GHz tripler, rather than at 600 or 1200 GHz.

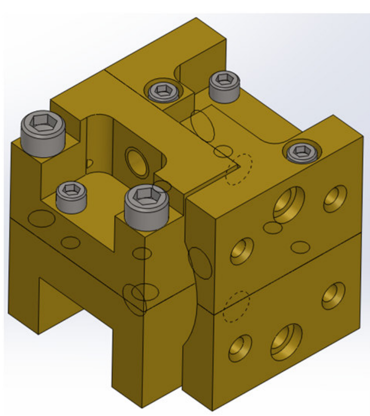


Fig 6. Combined/compact 1200 tripler/mixer block.

An additional advantage is that the design is compatible with the current 1200 GHz block design described in task 2. The original block (Figure 5) has a horn with two wide a beam to work with the optical bench. We are also going to try a second design for the 1200 that will also work with either the new tripler, or the previous version.

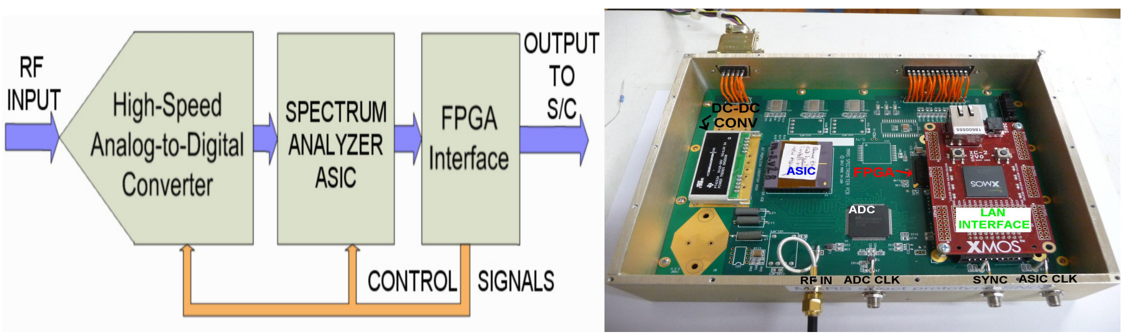
IV. Digital Back End Spectrometers.

The ASIC-based digital back end spectrometers have been received, and are currently being tested. These are of a new type of digital polyphase spectrometer recently developed for space-borne astronomical applications [8]. The principal of operation is similar to a windowed FFT. To improve the spectral resolution, the input data is first windowed using a 4-tap poly-phase FIR filter bank (PFB) that provides better spectral bin isolation and improved side-lobe isolation than a Hamming filter.

The spectrometer implementation has been re-designed for the TROPA program, specifically to allow for rapid switching between widely spaced spectral lines, while maintaining the original version's low power low mass properties.

Another change is to incorporate the interface to the control computer on a sub-board. In this case, the interface is to an Ethernet LAN port to simplify the rapid transmission of data to the host computer. The analyzer appears in Figure 7. Visible are the digitizer (ADC), spectrometer ASIC, and FPGA data processor. The new components (SYNC connector) and LAN interface are also shown.

Results from the first tests (at the manufacturer) are shown in Figure 8. A single signal at 60 MHz is shown, as well as the results from an on-chip vector test generator (VTG). The signal



(a) (b)

Fig. 7. New digital back end. (a) General block diagram. (b) Photo of spectrum analyzer. The ADC and polyphase ASIC are near center, and the new interface is at the right.

generator result shows that the digitizer (ADC) works and that the analyzer can correctly generate a single frequency spectrum. The VTG result shows that all 4096 spectral channels are working properly.

Figure 9 shows a similar test performed at JPL using our control software. A (somewhat noisy) signal generator produces a tone around 200 MHz tone as input. The right panel shows a zoomed in region about the tone.

The two next steps are to first, modify the code in the XMOS Ethernet interface to the raw ADC data to be output to the controller computer, then tune the ADC for best interleaving performance. For reliable operation we are using both halves of the ADC, each clocking on alternate halves of a 750 MHz signal to get the aggregate 1.5 GSps digitization rate. For this to work at these high data rates, the two ADCs must be "tuned" to match their characteristics to properties to yield a correctly digitized signal. To accomplish this, the raw data must be available to the computer in a pass-through mode for processing by the calibration software.

The second step is to modify the XMOS code again to provide the synchronization function that the instrument requires. Since the original version of the back end was designed for astronomical use, the spectra were simply accumulated for maximum sensitivity, for as long as

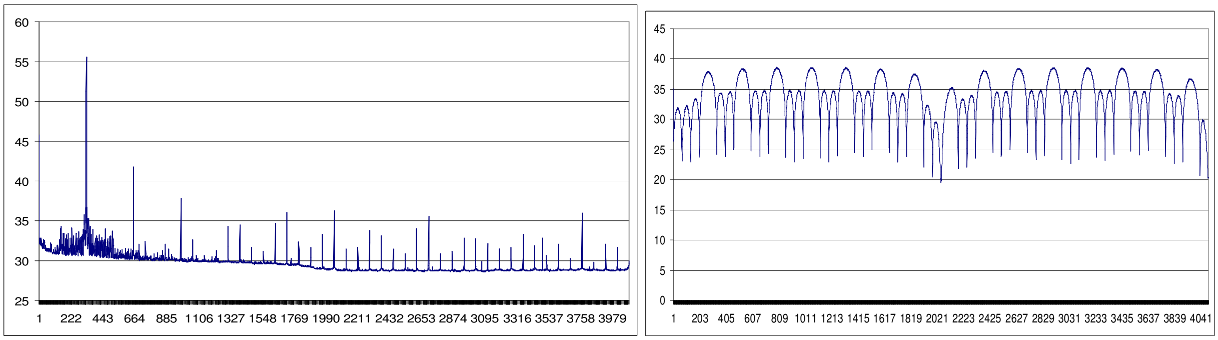


Fig. 8. New digital back end “first light”. At left, a 60 MHz -3 dBm signal is shown, with 183 kHz resolution (750 MHz bandwidth/4096 channels). At right a vector test generator result shows normal output from all channels.

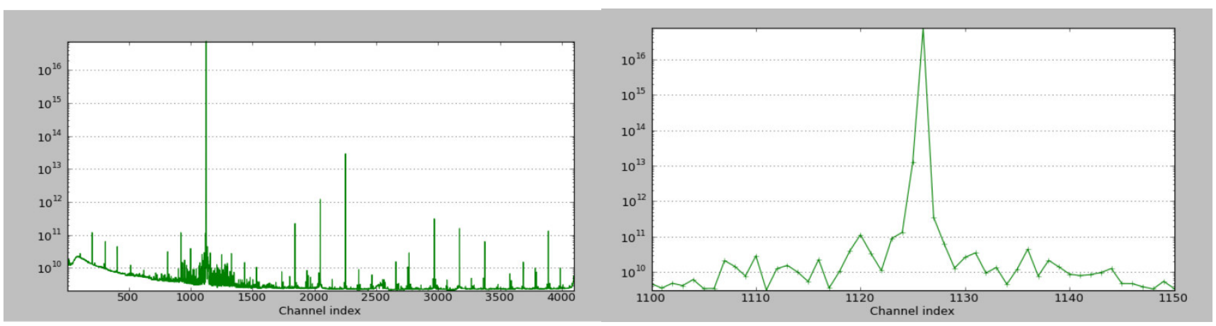


Fig. 9. Response of digitizer to 206 MHz tone input. Channel number = 4096*200MHz/750MHz=1125.

the telescope could be pointed at the target. The planetary version requires switching from line to line for about 100 ms per observation and the spectra must be accumulated separately for the different lines. This will be accomplished by use of an extra synchronization line to allow communication of the switching from the controller to the spectrometer.

The XMOS processor will be replaced by a rad-hard FPGA for the flight implementation. We are developing a next-generation ASIC polyphase spectrometer with 1.5 GHz bandwidth, 8192 channels, and embedded ADCs. The embedded ADCs provide the state-of-the-art in terms of power consumption, and will double the bandwidth of the spectrometer while reducing its power consumption to below 1 W.

V. Low-power, Fast Switching Wideband Synthesizer.

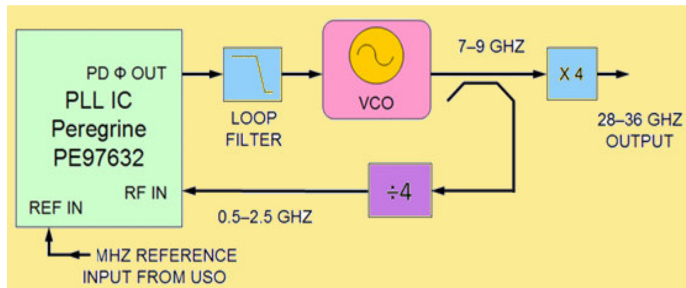
The synthesizers that pump the receiver LO multiplier chains must meet several critical requirements for this application:

1. Frequency range 28 – 36 GHz, to be multiplied by three into the 100 GHz band. The output is amplified and then multiplied by six to pump the two mixers.
2. Low power, well under 10 watts each.
3. They must be able to switch frequencies rapidly. Since the observation time is about 100 ms, a switching time of about 10 ms is necessary to not lose excessive observing time.

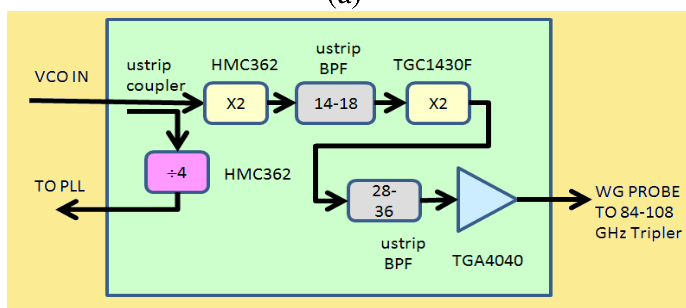
4. The phase noise must be low, since the phase error grows as 20log(N) dB for a multiplication ratio of N. Unlike most communications synthesizer, the main frequency range of concern is in the range starting from half the spectrometer channel bandwidth and higher. [9], [10].
5. Frequency steps (at the VCO band of 8 GHz) about 10 MHz. This is determined by the 750 MHz spectrometer bandwidth times the multiplication ratio to the highest frequency band, 36. Steps of 10 MHz at the synthesizer frequency yield 360 MHz steps at the 1200 GHz signal frequency.

The original intention was to procure commercial synthesizers. But due to the unusual requirements, we decided to prototype the synthesizer at JPL.

The block diagram is given in Figure 10(a). It utilizes a space qualified CMOS SOI fractional-N PLL, with a maximum input frequency of 3 GHz. In order to both meet the wide tuning range, and low phase noise above 100 kHz frequency offset, it was decided to base the synthesizer on a 7-9 GHz YIG tuned oscillator. Since this is well above the input frequency of the PLL, a ÷4 prescaler is used. Likewise, since the output frequency is 28 to 36 GHz, a ×4 multiplier will be used. This A single package will be used to house the prescaler and multiplier chain, whose block diagram is detailed in Figure 10b. It is based on commercial multiplier chips from Triquint and Hittite. This unit is currently being designed.



(a)



(b)

Fig. 10. 28-36 GHz synthesizer block diagram. (a) General block diagram. The output goes to a passive X3 tripler. (b) Synthesizer coupler-prescaler-multiplier.

The estimated power consumption of the synthesizer is 2.8 Watts, including the PLL (.13 W)

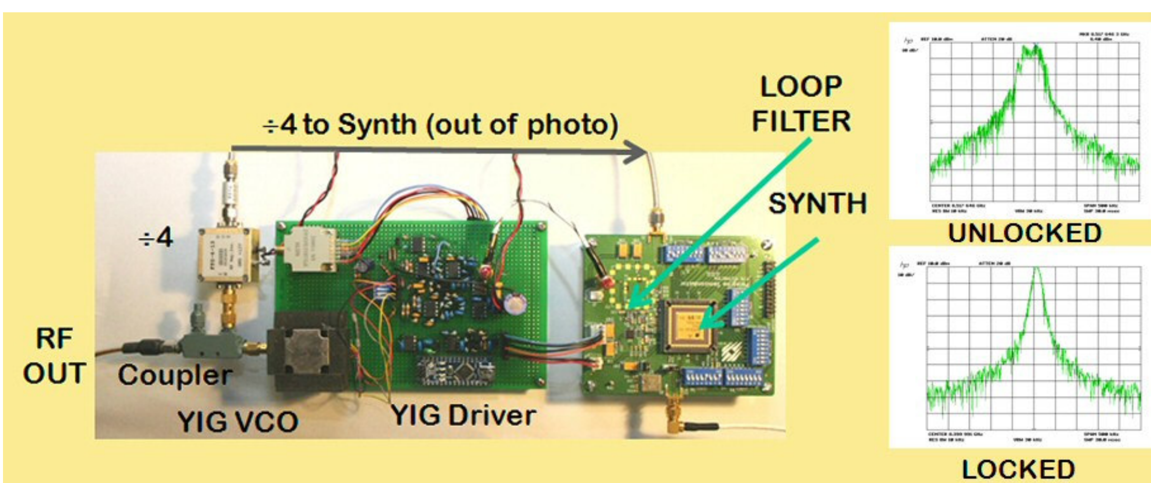


Fig. 11 Synthesizer prototype with spectrum analyzer plots showing effect of phase lock.

but *not* including the YIG-tuned oscillator (YTO). The oscillator power draw depends on the current through the YIG tuning coil. This can be minimized by using a permanent magnet YIG tuned oscillator (PMYTO). These have a permanent magnet designed to set the zero current frequency at the center of the desired band. This minimizes the total current needed to tune the YTO. The bias current for the YTO is specified as approximately 100 mA at 8.5 volts, hence 0.85 W.

The prototype synthesizer is based around an evaluation board for the PLL, and a prototype YIG driver board designed by the authors based on classic designs from HP spectrum analyzers and signal generators. The synthesizer also includes a small controller board based on an Atmel ATmega168 microcontroller. The prototype is shown in Figure 11, and until the multiplier is assembled, it uses a temporary coax based prescaler and sampling coupler. The current draw is about 0.4 A at 8.5 V, i.e. about 3.4 W, including the prescaler, which is a more power hungry version of the HM362 that has been purchased for the TROPA synthesizer. The synthesizer has been phase locked, and we are currently preparing to measure the phase noise. The initial spectrum analyzer scans (also in Figure 11) indicate the difference between the locked and unlocked YTO. The oscillator is sensitive to low-frequency noise, with a $1/f$ type integrating response [7]. Closing the loop clearly stabilizes the output signal as expected. The next steps are to program the microcontroller and narrow the loop bandwidth to fit the YTO. The expected phase noise profile is shown in Figure 12.

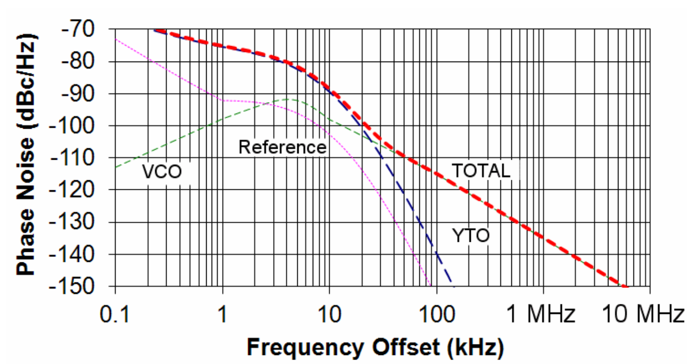


Fig. 12 Synthesizer phase noise estimate with individual contributions.

VI. Conclusion.

Intermediate results of a program to develop an instrument for Terahertz observation of planetary observations have been presented. Progress is proceeding along several technological fronts: Terahertz receiver front ends, back end spectrum analyzer, optical bench and wideband frequency synthesizer. Future publications will detail the completion of these tasks.

ACKNOWLEDGEMENTS

The research described herein was carried out at the Jet Propulsion Laboratory, California Institute of Technology, USA, under contract with the National Aeronautics and Space Administration including funding from the NASA Planetary Instrument Definition and Development Program.

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