A 188mW 2.0 GS/s Spectrometer Processor Enabling Low-Power THz Heterodyne Spectrometers for Planetary Exploration

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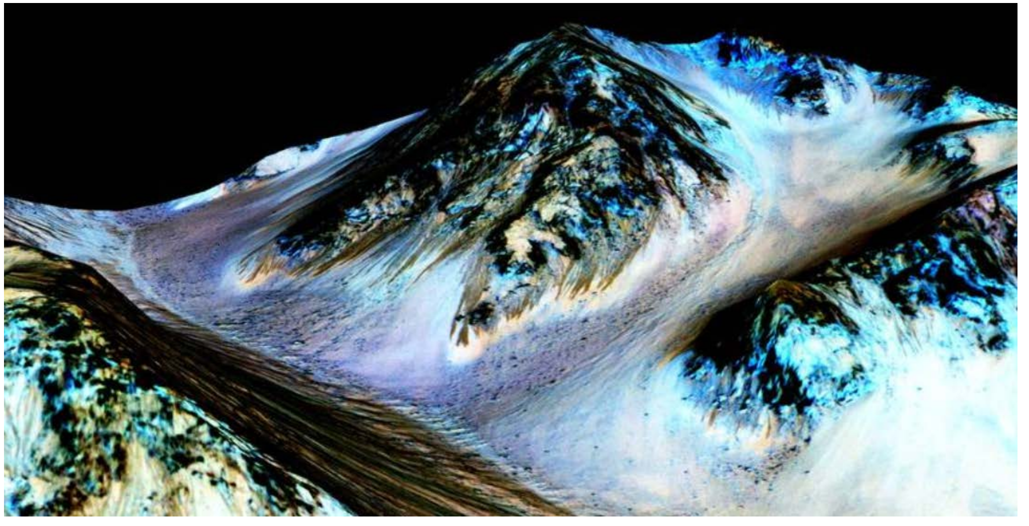
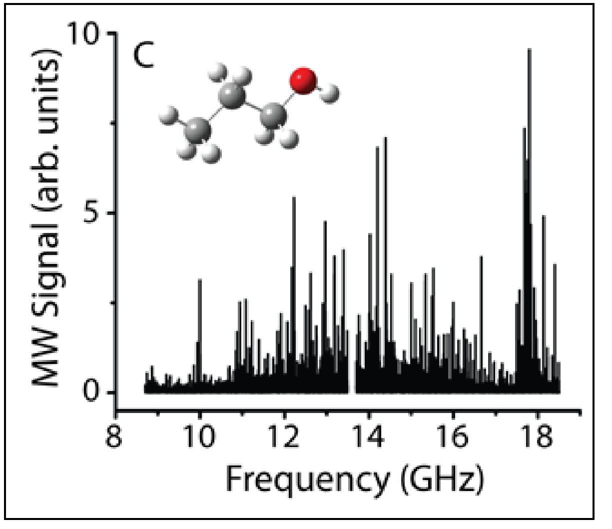
Overview

- Introduction to RF Spectrometers for Planetary Science
- Challenges of Planetary Instrumentation
- Top Level Instrument System
- Spectrometer Processor Design
- Science Validation and Results
- Conclusion
- References

Introduction RF Spectrometer Instruments

- NASA RF spectrometer instruments are used to investigate chemical composition of planets, asteroids and comets at microwave, millimeter-wave and even THz wavelengths.

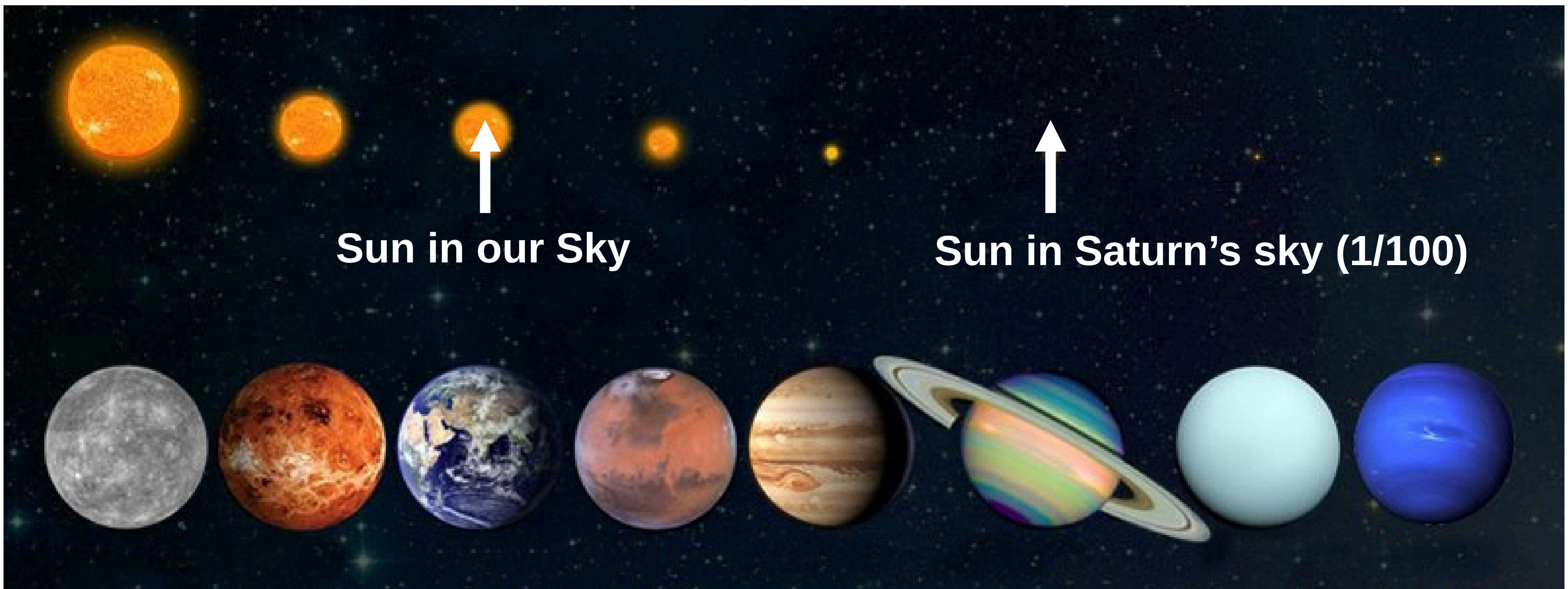




- Just yesterday the discovery of liquid water was announced on Mars!
- A spectrometer (possibly even the work presented here) will be sent in follow-on Mars missions to investigate this water to look for the building blocks of life (hydrocarbons, keytones,…) !

Challenges of Planetary Instrumentation

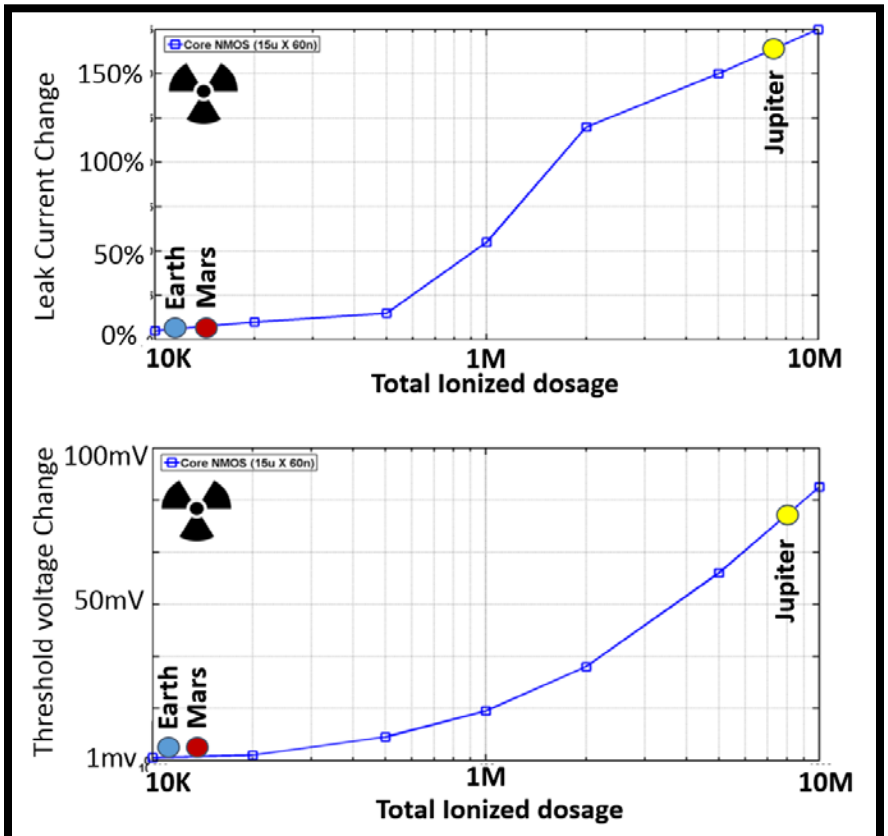
- NASA missions especially to outer planets have extremely limited payload resources in terms of electrical energy and size/mass.
- The journey to outer planets like Jupiter or Saturn can take up to 10 years… the distance from the sun is much greater than Earth, greatly limiting the available sunlight to power instruments and other electronic systems.



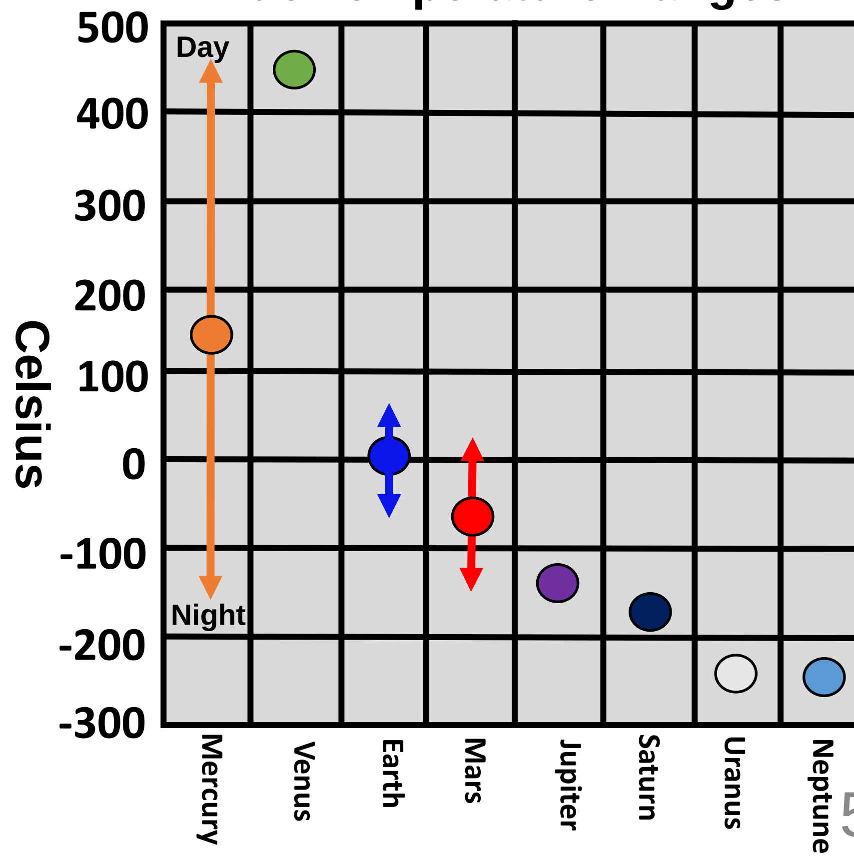
CMOS for Space Instrumentation

- **Given the power and size/weight limitations, highly integrated SoC solutions become attractive for planetary space instruments.**
- **CMOS solutions still need to be designed to accommodate the deep space environment.**

High Levels of Cosmic Radiation



Wide Temperature Ranges



Architecture of RF Spectrometer Instruments

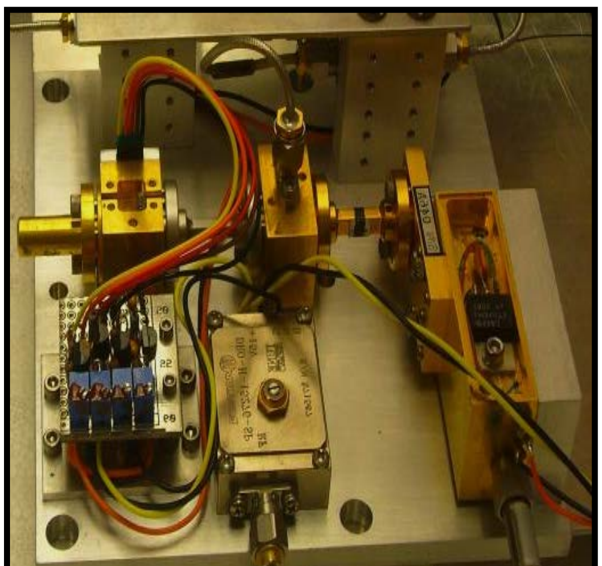
Spectrometer Receiver (RF)

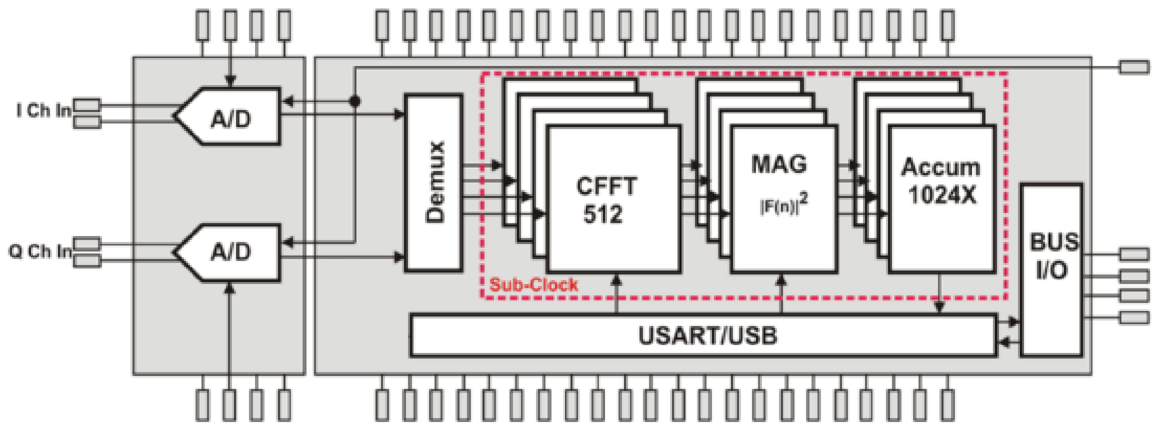
Front-End Receiver → IF Signal Filtering

Spectrometer Processor (focus of this work)

Digitization → Spectral Computation → Averaging or Accumulation

Photo of a 500-600 GHz JPL Spectrometer Receiver

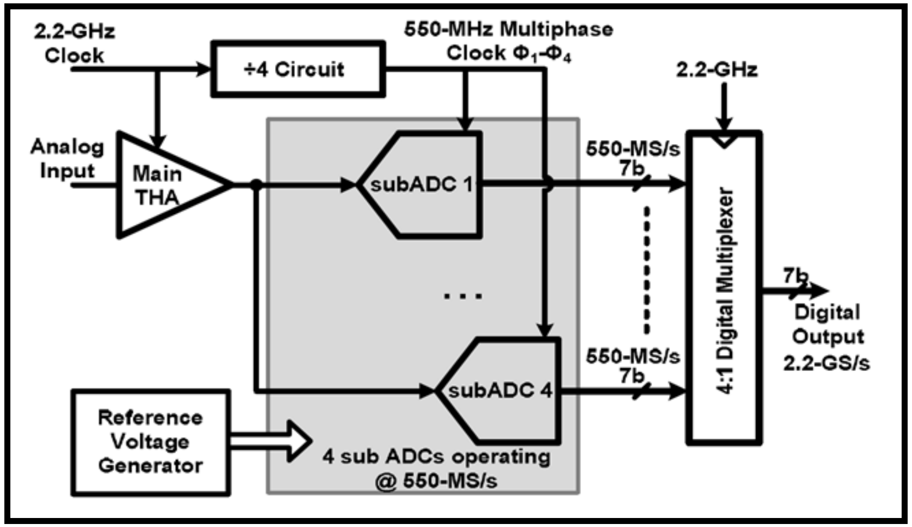




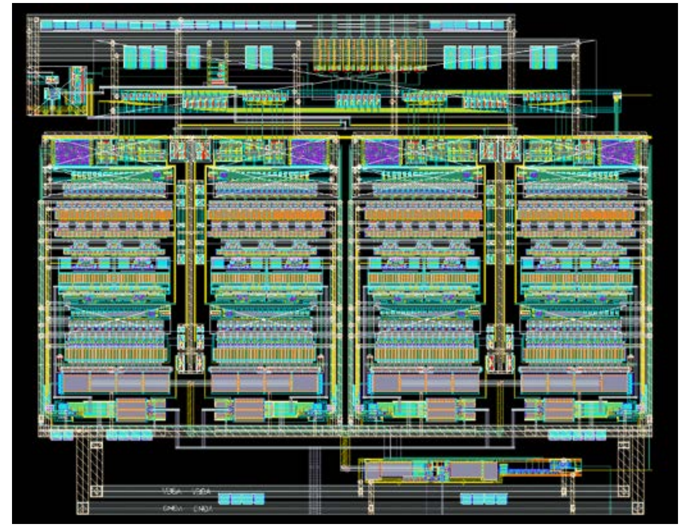
- **High frequency receivers capture incoming radiation and the spectrometer processor then computes the FFT (spectrum) of and averages to increase the final SNR.**

7b 2.0 GS/s ADC used in Our Spectrometer Chip

ADC Top Level Block Diagram



ADC Block Layout



- **The ADC used in our spectrometer processor is a sub-ranging interleaving by 4X flash ADC with 5.5 effective bits.**
- **The core ADC design was previously reported at CICC in 2011 and the previous publication contains all the key design details and performance measurements (SFDR, ENOB, SNDR, …) :**

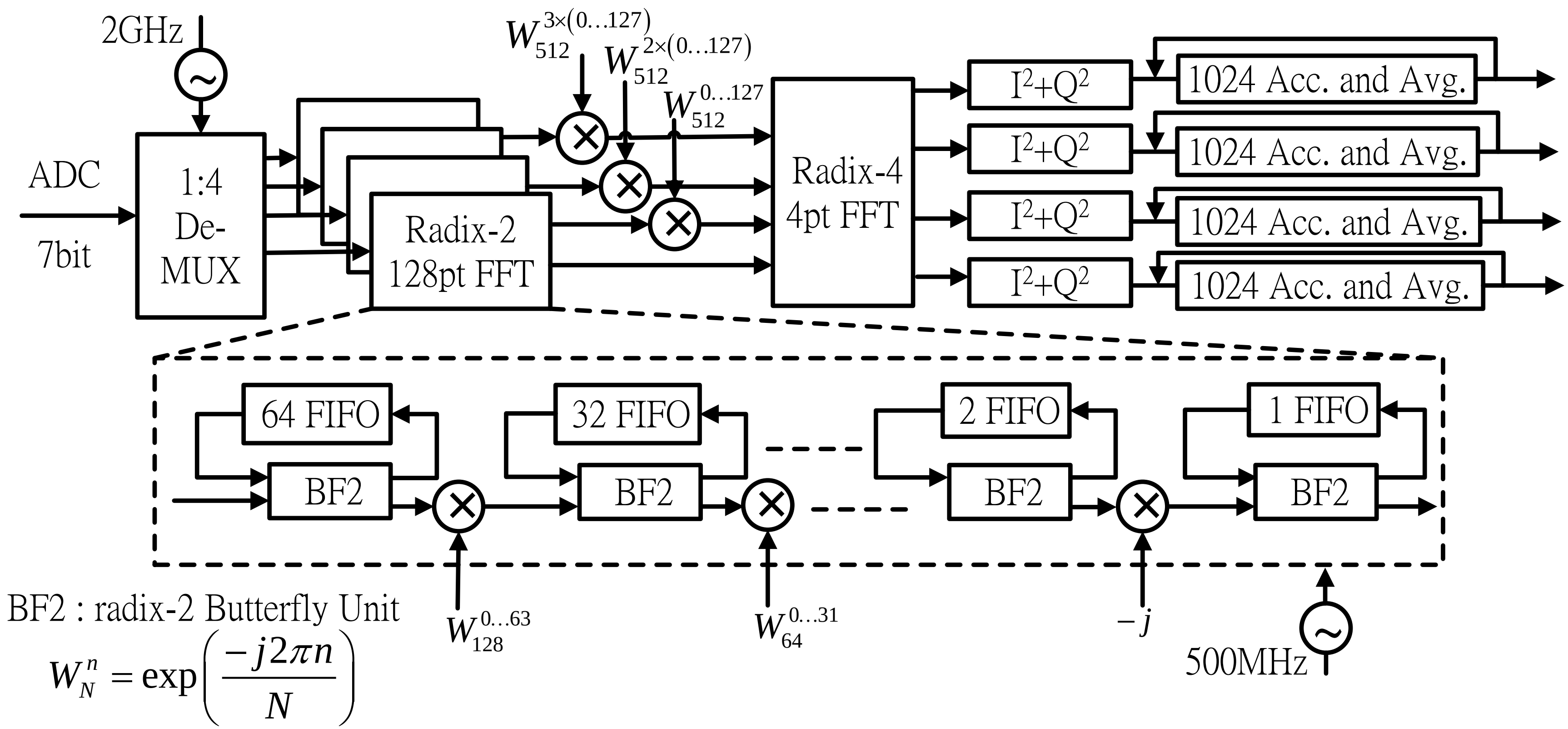
Gigabit (CICC

I-Ning Ku, et-al, "A 40-mW 7-bit 2.2-GS/s Time-Interleaved Subranging ADC for Low-Power Wireless Communications in 65-nm CMOS", IEEE Custom Integrated Circuits Conference 2011), Sep. 2011

Spectrometer Chip 2.0 GS/s FFT Processor

- **The spectrometer digital core consists of two main operations, PSD computing and spectral bin averaging**
- **The 2.0 GHz 512 FFT processor at 65nm with pipelining provides a nearly loss-free time to frequency transformation at small area and low power requirements for space application**
- **To meet digital timing constraints of 65nm CMOS, 4-parallel approach is adopted to reduce the core FFT clock, the data sampling rate of each sub-FFTs is at 500 MHz**
- **To compensate the FFT truncation error from fixed-width multipliers, rounding and scaling is applied at each FFT output stage which maintains the input and output at 14-bit width with 60dB SQNR**

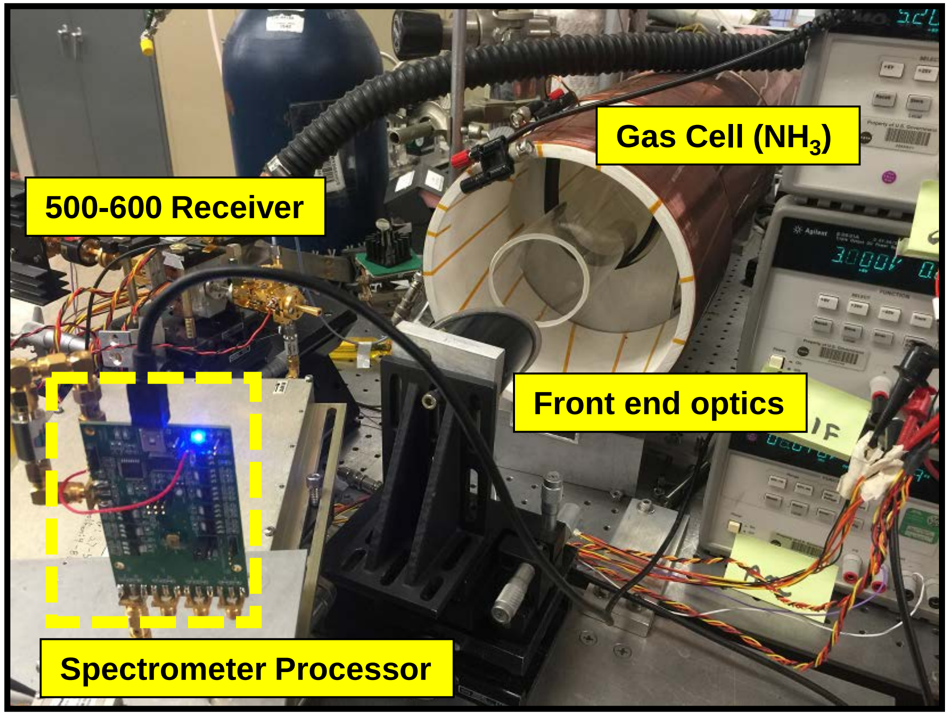
FFT Processor Block Diagram

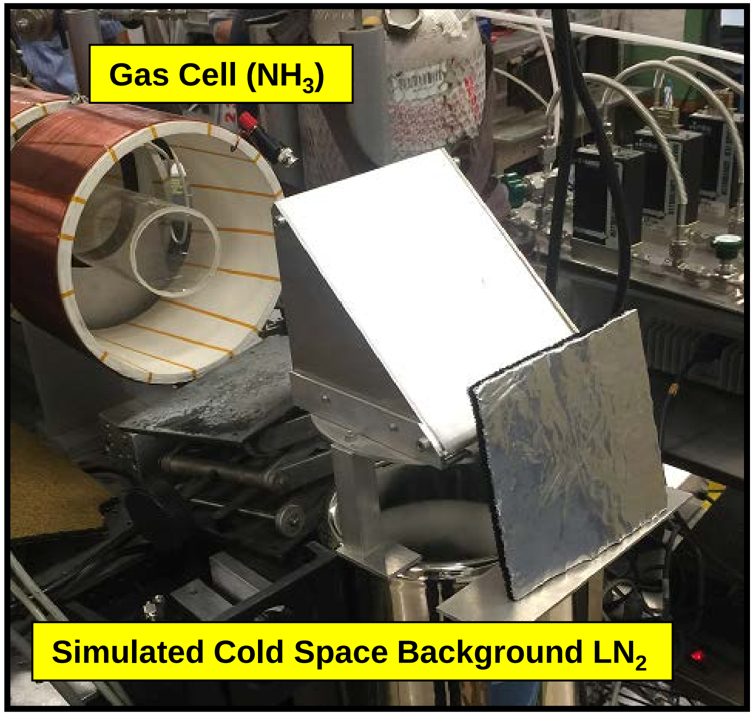


- **Architecture uses 4-parallel 128 point FFTs implemented with Radix-2 butterfly units followed by a final 4 point FFT implemented with Radix-4 buttefly units.**
- **Magnitude (I^2 +Q^2) is computed in final FFT stage and accumulated up to 1024 times to improve the final SNR of the spectral estimate.**

Spectral Processor Science Validation

- To evaluate the performance of the spectral processor in a representative environment we package the chip on a PCB with supporting circuitry and integrate with a JPL 500-600 GHz Receiver.

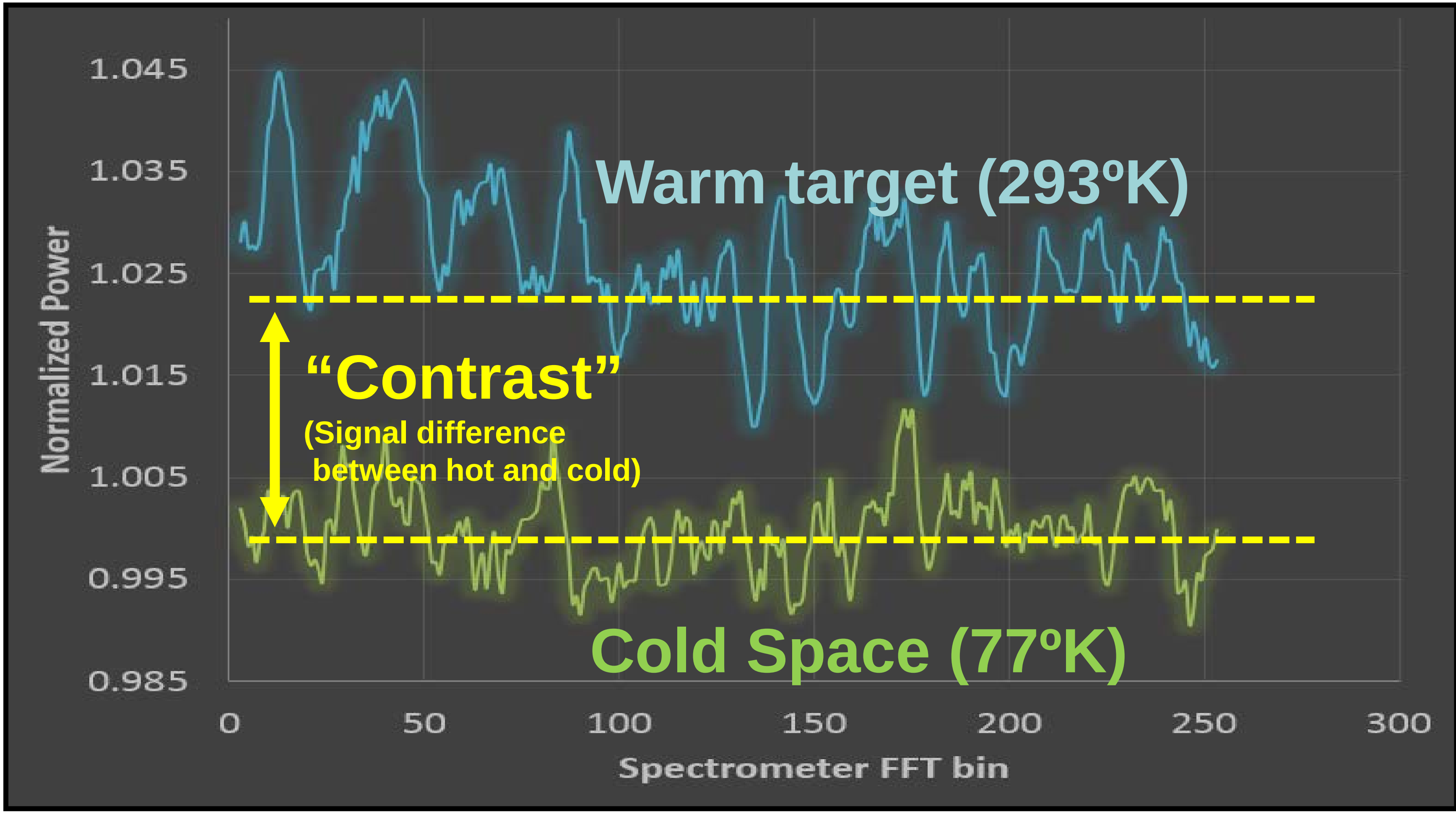




- A gas cell is placed in front of the receiver optics which allows various gasses to be placed in the path of receiver's field of view at varying concentrations, allowing us to duplicate the measurements to be performed in space.

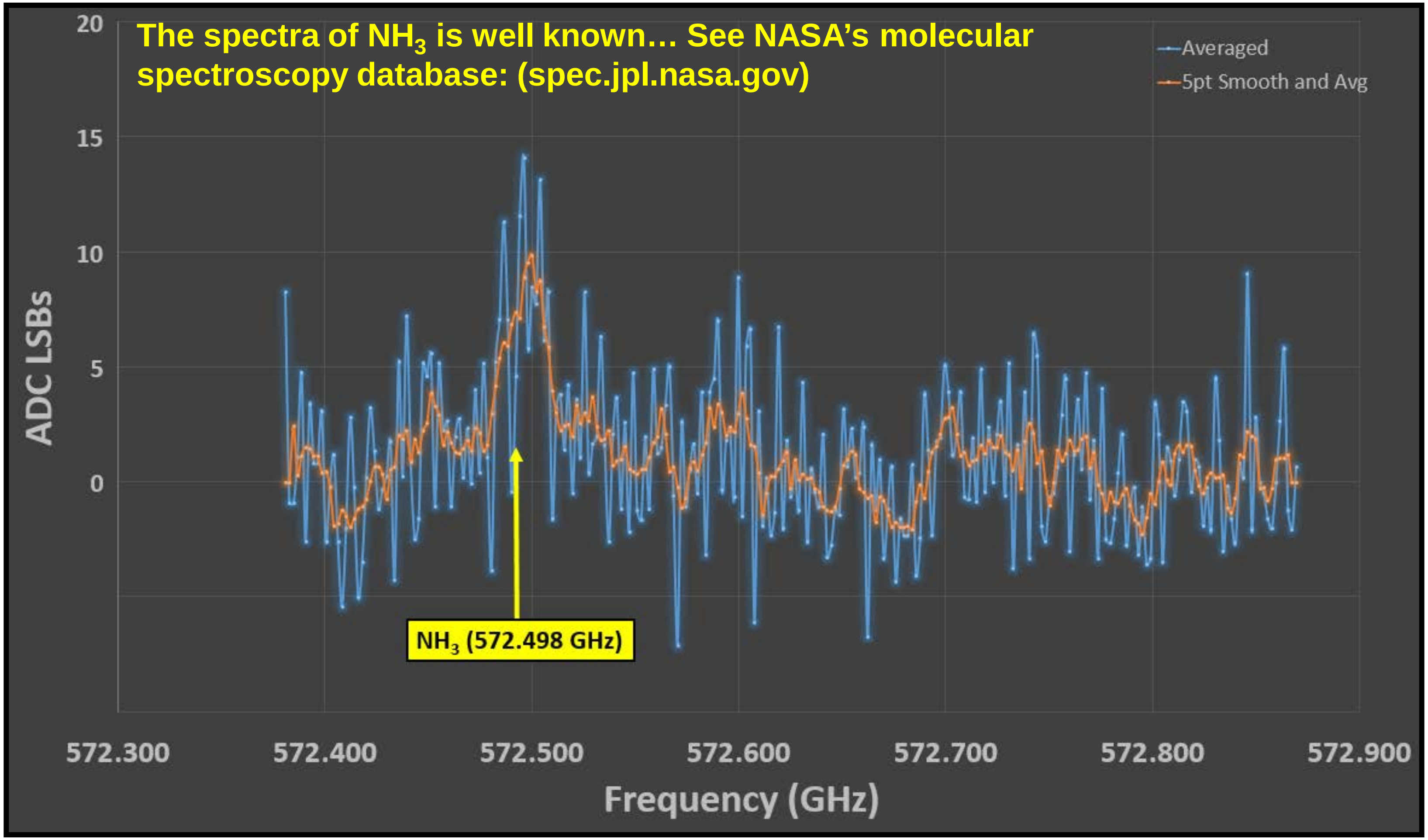
Spectral Processor Contrast Check

- We first capture the output of the spectrometer instrument with liquid nitrogen (77ºK) in the background, and then with a room temperature target to provide calibration data for composition measurements.

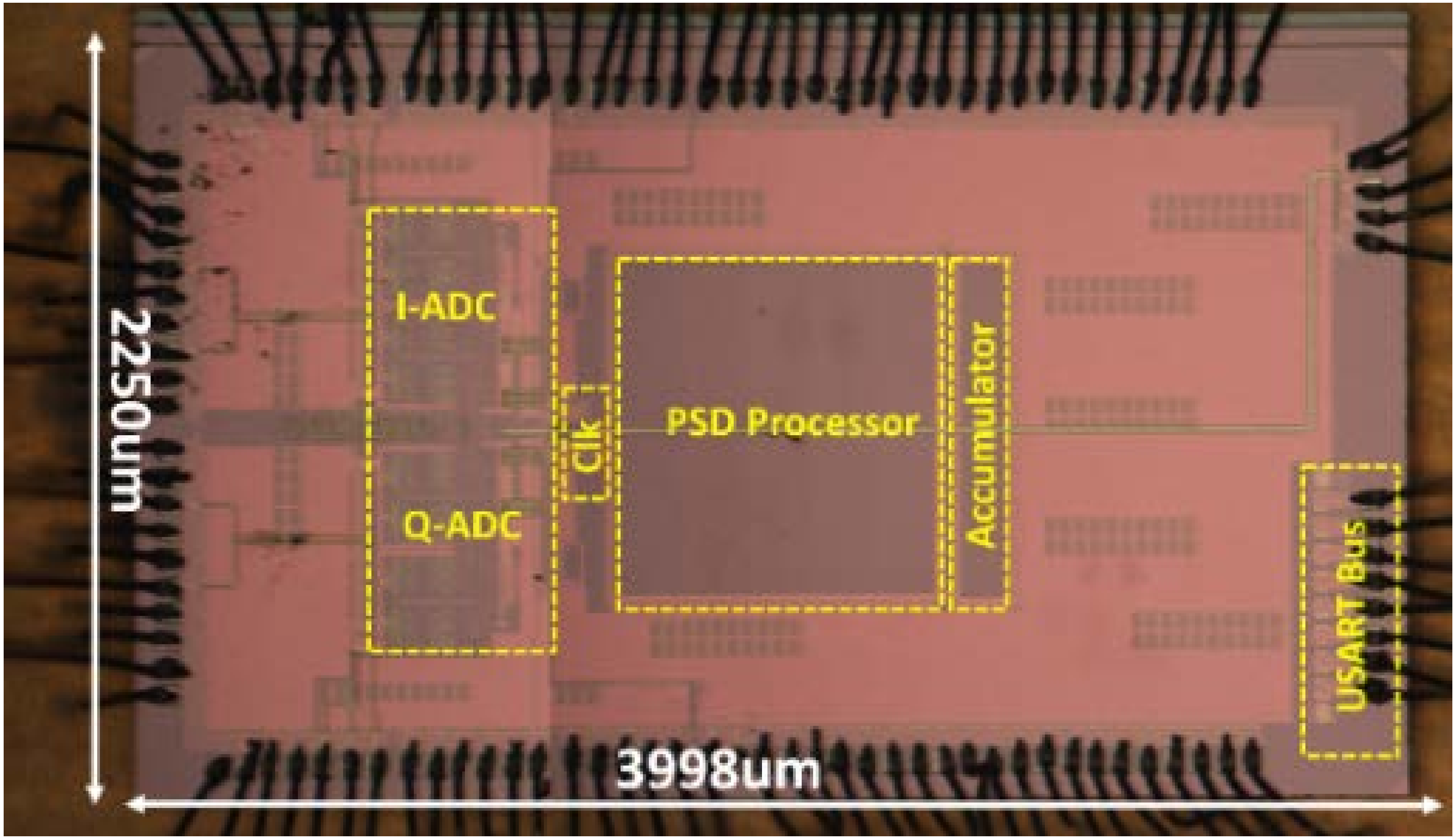


Spectral Processor Sample Gas Detection

- Next we add ammonia gas (NH_3) in the test chamber at a detection pressure of approximately 0.5 mTorr. By again capturing the spectrum and de-embedding the hot cold calibration we reveal the absorption spectra.



Spectral Processor Die Photo



- The spectral processor chip contains an integrated USART (SPI) type control bus to control averaging and other sequencing functions as well as readout of the captured data.
- The chip is compact and assembled using conventional wirebonding.

Spectral Processor Die Photo

	This work	[1] CICC '09	[2] ICSPS
Bandwidth	1000 MHz	750 MHz	205 MHz
Implementation	65nm CMOS	90 nm CMOS	FPGA
FFT Point	512	4096	1000
Integrated ADC	Yes	No	No
Total Power	188 mW	1.5 W	5W
FOM (pts X BW) / mW	2.72	2.05	0.041

- Comparing to other CMOS based spectrometer processors, we highlight that this is the first work with integrated ADCs and the highest reported figure of merit.
- Also the first reported CMOS spectrometer processor coupled to a full instrument and shown to detect real chemical spectra.

Conclusions

- A spectrometer processor implemented in 65nm CMOS technology which is capable of supporting future THz spectrometer instruments for planetary exploration was demonstrated.
- The spectrometer processor consumes 188 mW of power and occupies 9.0 mm2 of silicon area, making it suitable for planetary missions where size weight and power is limited.
- First integrated low power/area GS/s spectrometer SOC validated with physical detection of chemical composition and operating in a space like environment.
- Future spectrometer processors are being developed by our UCLA-JPL partnership with even higher spectral resolution and wider bandwidths.

References

[1] B. Richards, et-al, "A 1.5GS/s 4096 spectrum analyzer for space-borne applications" IEEE CICC 2009, pp 499-502.

[2] L. Dong, M. Wang, S. Shuobiao, "A new digital spectrometer for low frequency solar radio observation based on FPGA," ICSPS, vol.1, no., pp.119-126, July 2010

[3] I-Ning et-al; "A 40mW 7bit 2.2GS/s Time-Interleaved Subranging CMOS ADC for Low-Power Gigabit Wireless Communications", IEEE Journal of Solid-State Circuits, vol. 47, no. 8, pp. 1854-1865, Aug. 2012.

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