Update on the Stratospheric Water Inventory – Tomography of Convective Hydration (SWITCH, IIP-2016) project

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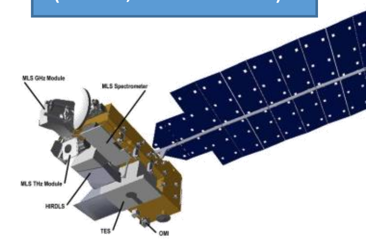
Introduction and context for project

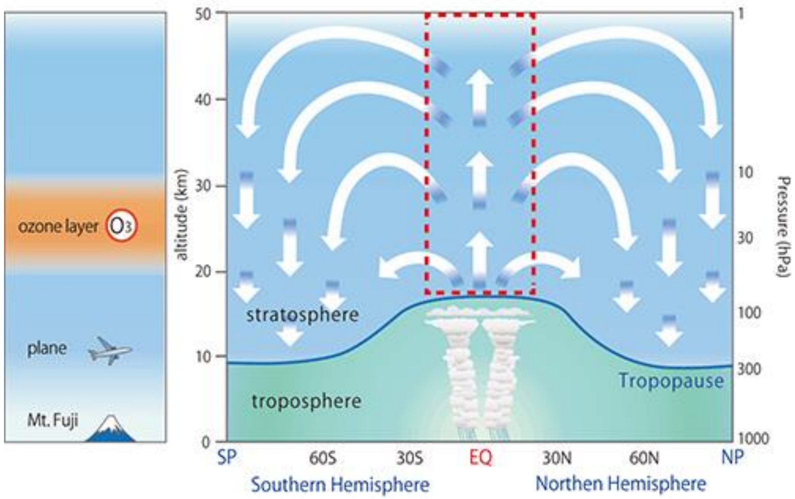
- Although current and previous limb and occultation sounding instruments have enabled key discoveries related to Earth's upper troposphere, stratosphere and mesosphere, many outstanding questions remain
- Resolution of these questions demands:
  1. Continuation of the observation record from sensors such as the Microwave Limb Sounder (MLS) on Aura, to quantify the long-term evolution and interplay of processes affecting climate, ozone layer stability and air quality
  2. Selected high resolution observations of specific species/regions to quantify the details of particular processes having a potentially large impact
- The "Compact Adaptable Microwave Limb Sounder" (CAMLS, NASA IIP-2013) project is developing a potential instrument for #1
- The SWITCH measurement concept is aimed at an important and timely example of #2: high spatial resolution (~500 m vertical, ~10 km along-track) observations of lower stratospheric water vapor
- The specific science goal is to quantify the extent to which convectively injected "plumes" of significantly enhanced water vapor in the lower stratosphere contribute to overall stratospheric humidity
- This is important as stratospheric water vapor is a strong contributor to the greenhouse effect

Upper Atmosphere Research Satellite (UARS, 1991–2005).



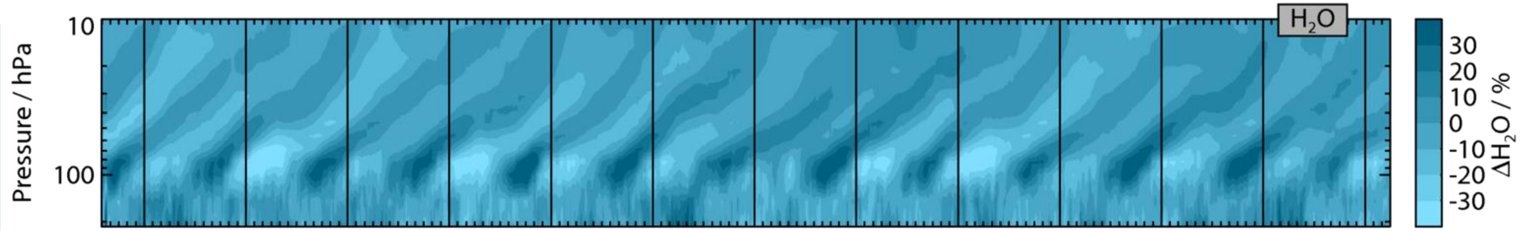
Aura (2004–).

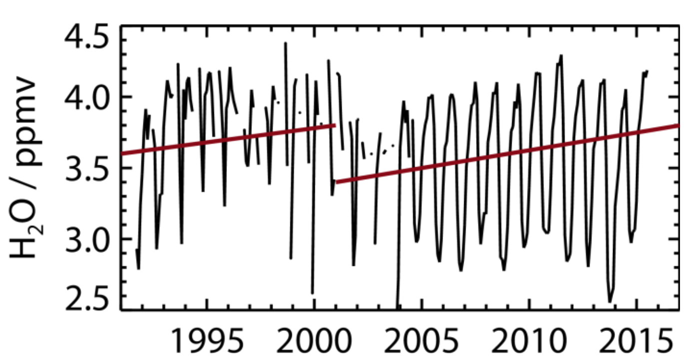
Stratospheric water vapor variability and its impacts



- The main mechanism controlling stratospheric water vapor (SWV) is understood to be the "freeze drying" air experiences as it passes through the tropical tropopause on its way to the stratosphere
- This gives rise to the so-called SWV "tape recorder"

Anomalies in MLS 10°S–10°N water vapor, showing the "tape recorder" signal.



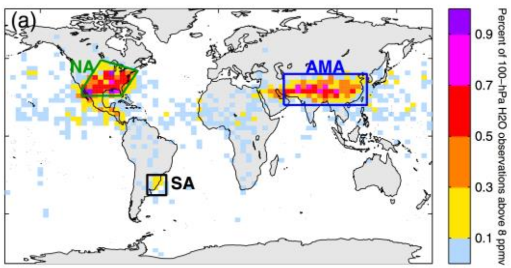


- SWV noticeably "dropped" in 2000
- This is estimated to have reduced warming in the subsequent decade by 25% compared to that expected from CO_2 increases alone [*Solomon et al., Science,* 2010]

Multi-satellite record of ~16 km, 50°S–50°N SWV. Red lines roughly indicate 2000 drop.

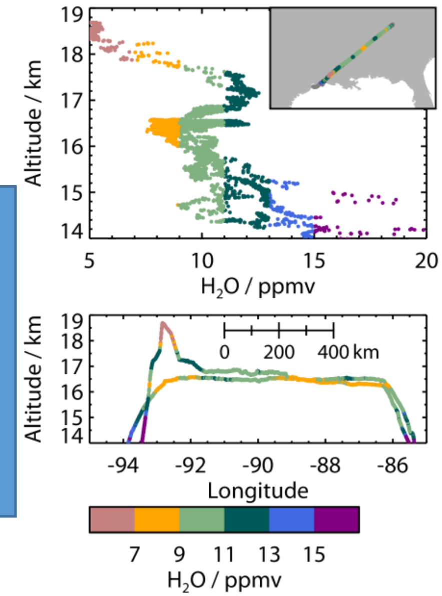
Enhanced SWV plumes in the lower stratosphere

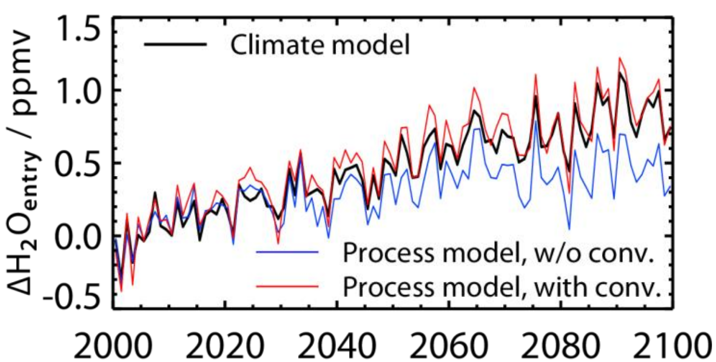
- However, significantly enhanced water vapor plumes have been observed in the lower stratosphere (mostly over the North American and Asian summer monsoons) by both aircraft and satellite



Fraction of Aura MLS ~16 km H_2O observations above 8 ppmv (purple = 0.9%).
MLS confirms North American and Asian monsoons as main regions for convective overshoot, but lacks resolution to quantify their impact on SWV budgets.

Aircraft in situ observations of an August 2007 SWV plume at ~17 km over North America. Typical background values above 16 km are ~3–5 ppmv.



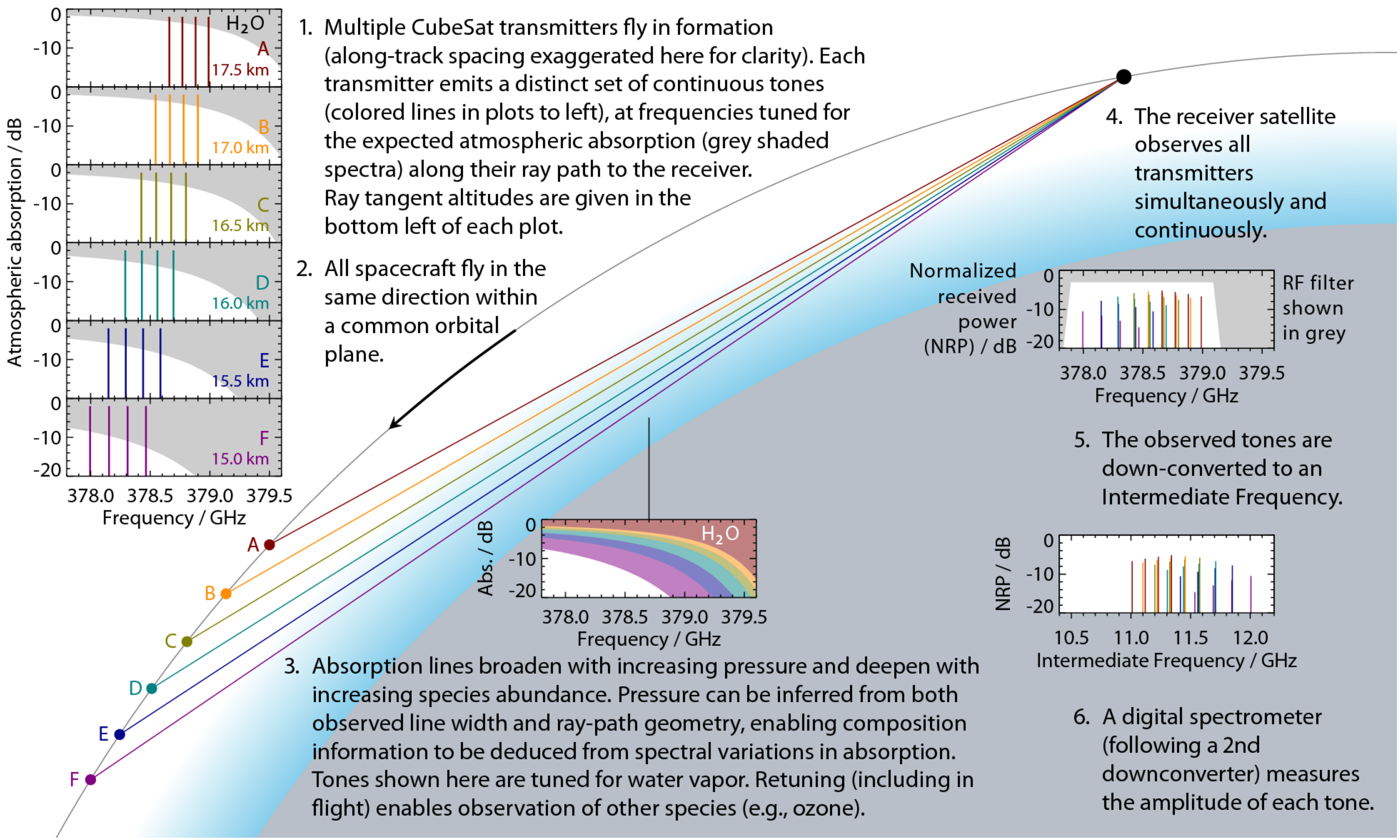


- Model calculations indicate that such convective overshooting (expected to increase in a warming climate) may contribute significantly to SWV trends

Future changes in SWV predicted by the GEOSCCM chemistry-climate model (black), and by a process model with (red) and without (blue) convective overshooting.

- The true degree to which these plumes contribute to global SWV budgets is unclear and can only be quantified with high-resolution observations with continental-scale or better coverage

The SWITCH measurement concept



1. Multiple CubeSat transmitters fly in formation (along-track spacing exaggerated here for clarity). Each transmitter emits a distinct set of continuous tones (colored lines in plots to left), at frequencies tuned for the expected atmospheric absorption (grey shaded spectra) along their ray path to the receiver. Ray tangent altitudes are given in the bottom left of each plot.

2. All spacecraft fly in the same direction within a common orbital plane.

3. Absorption lines broaden with increasing pressure and deepen with increasing species abundance. Pressure can be inferred from both observed line width and ray-path geometry, enabling composition information to be deduced from spectral variations in absorption. Tones shown here are tuned for water vapor. Retuning (including in flight) enables observation of other species (e.g., ozone).

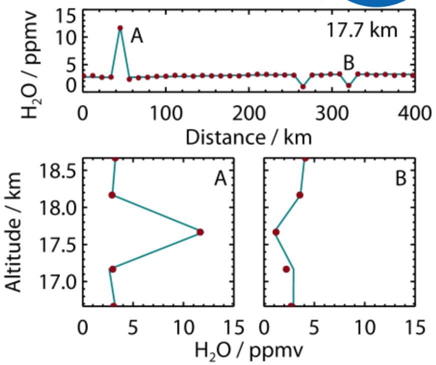
4. The receiver satellite observes all transmitters simultaneously and continuously.

5. The observed tones are down-converted to an Intermediate Frequency.

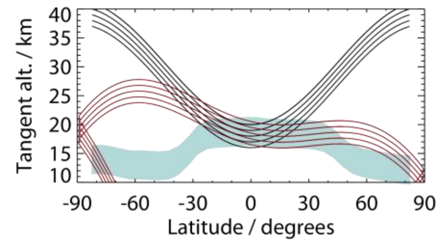
6. A digital spectrometer (following a 2nd downconverter) measures the amplitude of each tone.

SWITCH measurement details

- SWITCH vertical resolution is roughly set by transmitter spacing
- Horizontal resolution is bounded by integration time and affected by signal to noise and radiative transfer considerations
- Signal to noise is dominated by the transmitter tone power and the gains of the transmit and receive antennae
    - A narrower transmit beam provides greater received power
    - But narrower beams demand greater transmitter pointing accuracy
    - We are targeting a 15 cm antenna, equating to 0.35° pointing accuracy
    - A 15 cm receiver antenna, combined with 1 mW/tone transmit power gives 32 dB SNR end-to-end
- Orbital altitude (600 km assumed here) has little impact, as the $1/r^2$ loss can be compensated for by increasing antennae gains
- Retrieval simulations (upper right) show that this SNR enables tomographic water vapor observations with 500 m vertical, 10 km along-track resolution
- Earth's oblateness (being 44 km wider at the equator than pole-to-pole) complicates the measurements. Elliptical orbits (lower right) can optimize the coverage



Teal lines show horizontal (upper) and vertical (lower) cross sections of of a model SWV field with simulated small scale plumes. Red points show same field "measured" by SWITCH at 500 m x 10 km resolution.



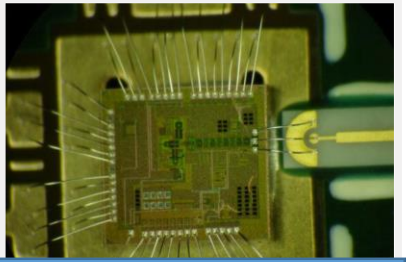
Altitude/latitude coverage for example circular (black) and elliptical (red) orbits. Shading shows the typical location of the lowermost 5 km of the stratosphere

SWITCH Instrument Incubator project goals

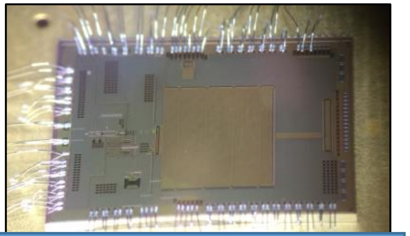
- Develop a complete "transmitter instrument package" in ~3U of a 6U CubeSat form factor
  - Includes CMOS devices for generating various tones (10–11 GHz and 90–100 GHz)
  - Output four RF tones in the 380 GHz spectral region
  - Transmit using a simple parabolic antenna
  - Build three transmitter instruments (one for balloon tests, one for vibration/radiation tests, one to retain as backup)
- Develop a complete "receiver" instrument package, again targeting a 3U CubeSat form factor
  - Develop a 380 GHz Schottky-diode mixer based on proven designs
  - Use the same CMOS components employed in the transmitter to generate the Local Oscillator
  - Develop spectrometers (new ASIC-based spectrometer as "primary", FPGA as "alternative") for quantifying tone amplitudes
- Perform end to end testing of the SWITCH measurements
  - In ground-to-ground configuration at the JPL 1 km range
  - In a high altitude balloon-to-balloon configuration using a pair of "small" (by CSBF standards) balloons
    - + Develop common gondola package for transmitter and receiver

Key enabling technology – CMOS Systems on Chip

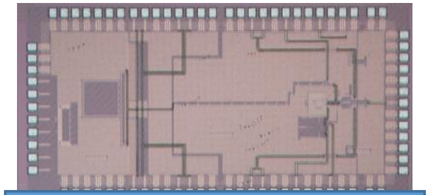
- This project makes extensive use of new CMOS "System on Chip" (SoC) technology to achieve the needed power/volume/mass reductions
  - The term "System on a Chip" refers to a Chip that includes not only analog and digital circuitry (as in a "mixed signal Application Specific Integrated Circuit, ASIC") but also radio frequency (10–100 GHz in our case) components
- The SoCs developed and employed for the SWITCH project include:
  - A tunable 90–100 GHz tone generator that forms the core of the transmitter system, and also provides the LO for the receivers
  - A 4096 channel digital spectrometer with 1 to 3 GHz bandwidth
    - + SWITCH uses the 1 GHz configuration, other projects are using up to 3 GHz
  - A tunable 10–11 GHz tone generator that (in a "backup" configuration of the transmitter) works with a set of combiners and the above oscillator and a mixer to produce discrete tones
- All three of these have been developed, fabricated and tested, (the spectrometer under other programs), with a revision of the 90–100 GHz oscillator, providing greater amplitude control, ready for integration on to the "transmitter board"



90–100 GHz oscillator
1 mW output power
Uses only 200 mW
1.6 x 1.6 mm



4096 channel 3 GHz bandwidth spectrometer with integrated ADC
1.5 W, 5mm x 3mm

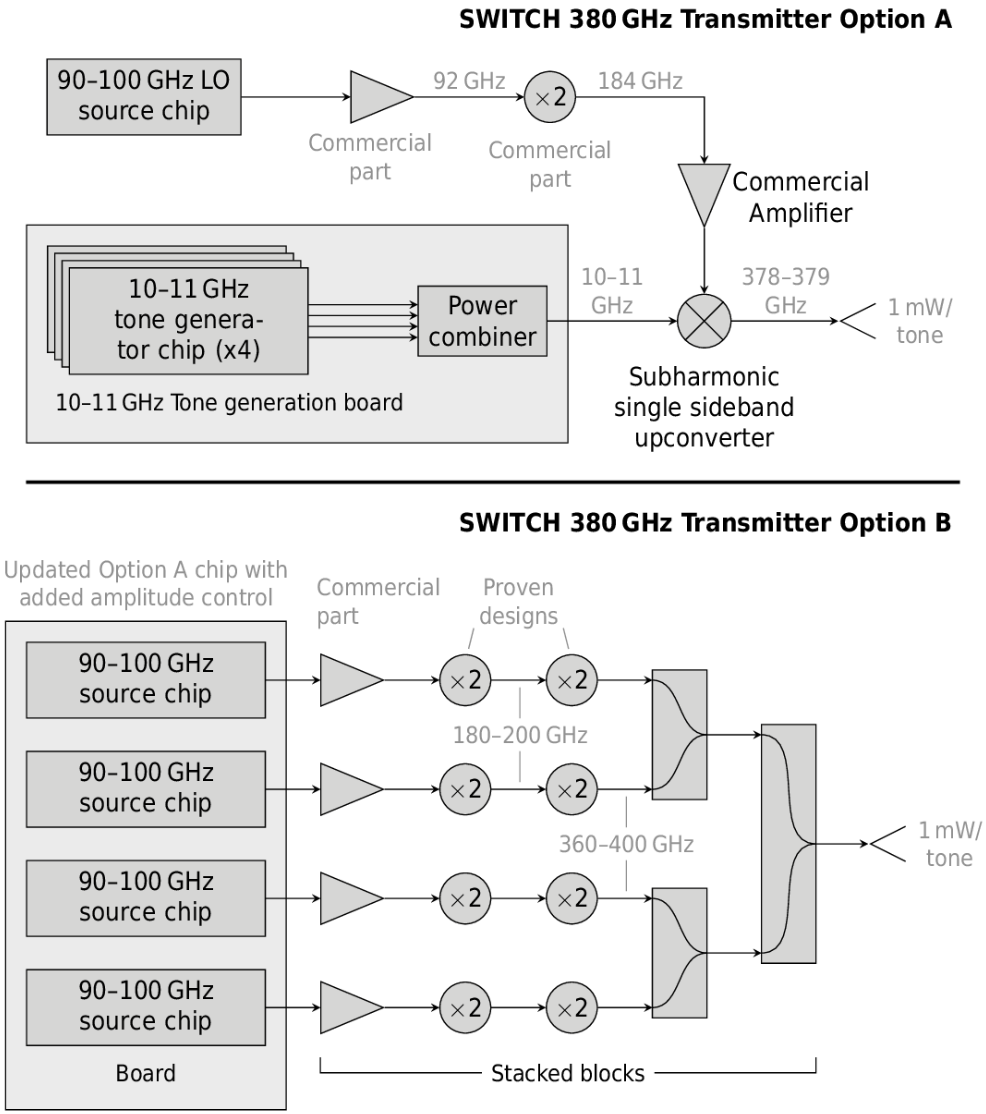


10–11 GHz oscillator
1 mW output power
Uses 500 mW

An early challenge – Radio Frequency allocation

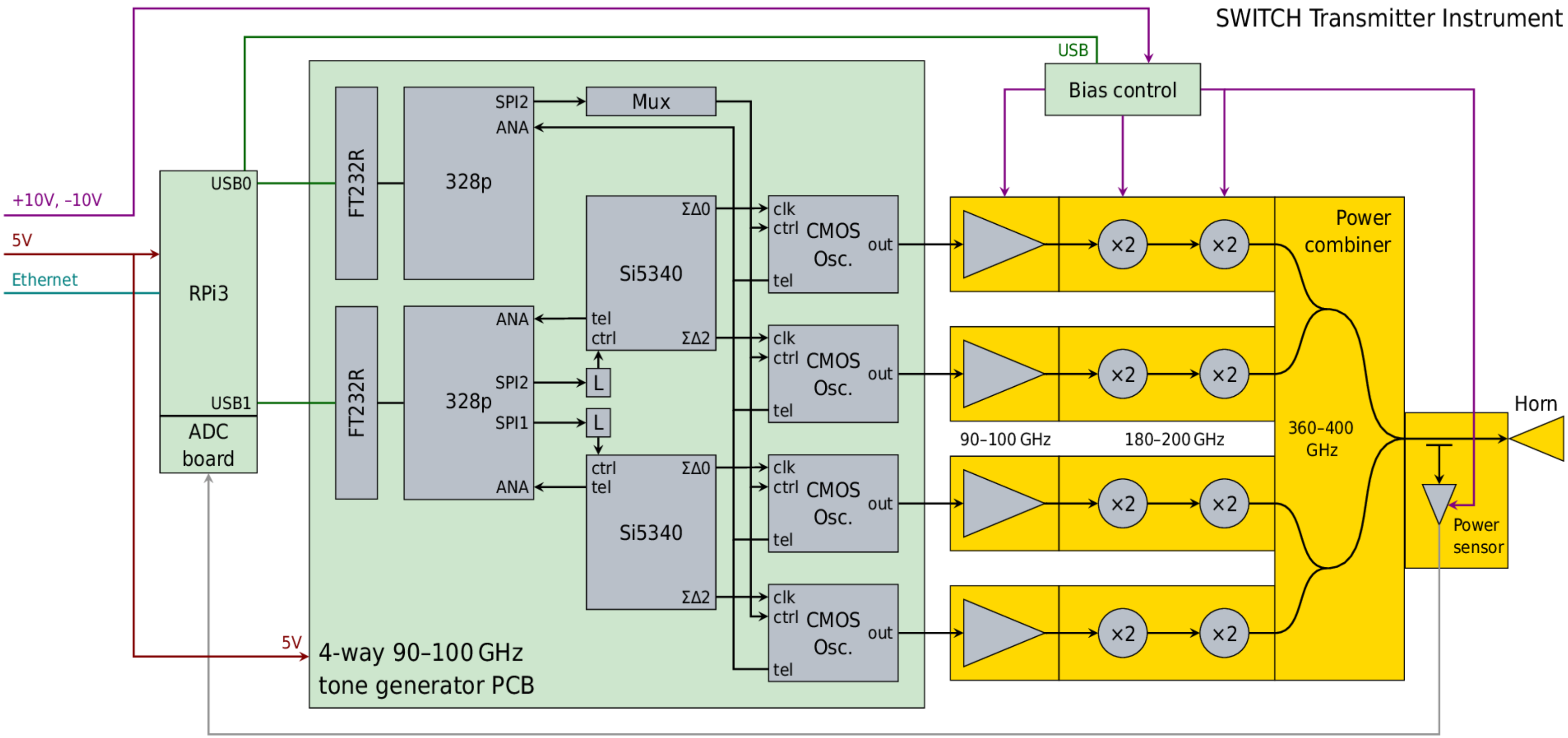
- Our original concept for SWITCH involved transmission around the 183 GHz water vapor line
- We did anticipate having to negotiate permissions for such transmission
  - This line is important for many observations (not least our own spaceborne "Microwave Limb Sounder", MLS, instruments)
  - However, given the limb transmitting/viewing geometry, we were confident that we could demonstrate no impact on those measurements, and seek a waiver for existing restrictions
  - We were aware of others (e.g., Robert Kursinski and colleagues) having successfully completed such negotiations, so were confident that a viable path could be found
- However, we did not anticipate that NASA's own spectrum allocation office would take a stricter stance than that of the wider US government
- Accordingly, six months into the project, we revised our plans to instead measure in the 380 GHz region
  - Currently the spectrum above 275 GHz is deemed "unregulated" though technology advances and competition and rapidly increasing interest in this region
- This frequency allows us to still use our 90–100 GHz fundamental oscillators with the addition of a further doubler stage

SWITCH transmitter – two approaches being developed



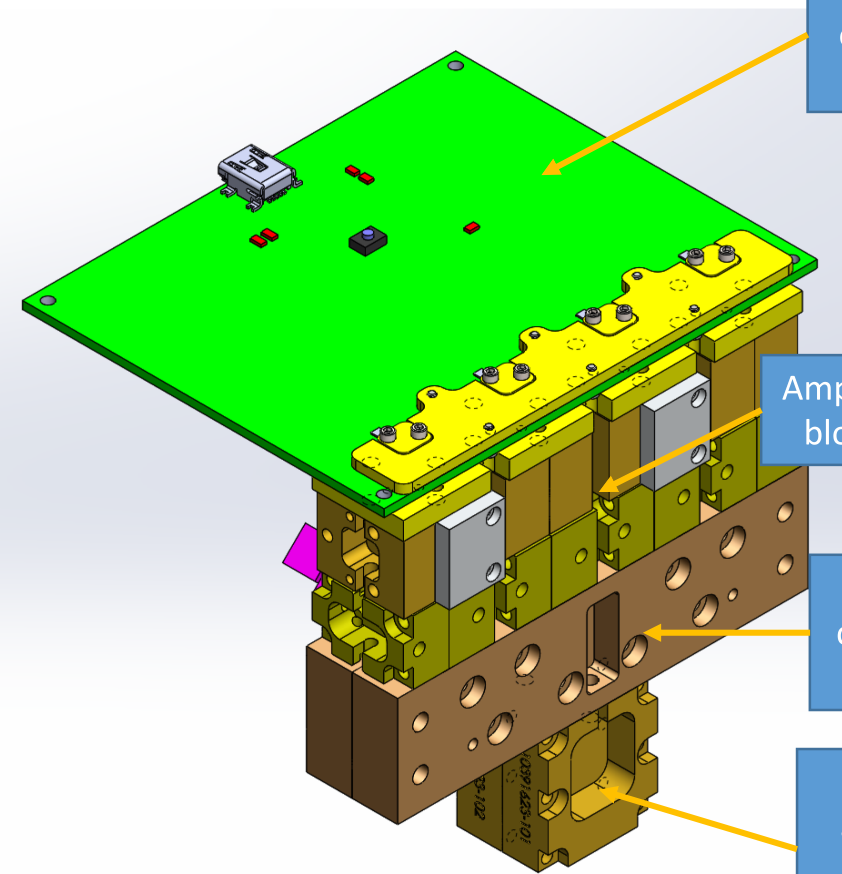
- The original (183 GHz) transmitter approach followed "Option A", though with a 193 GHz fundamental mixer rather than the subharmonic one used for the new 380 GHz approach
- However, the subharmonic mixer may prove unable to suppress spur tones as well as the originally planned fundamental mixer would have done
- Accordingly, we are also developing an "Option B" approach
- This simply amplifies the 90–100 GHz tones generated by the CMOS oscillators and then quadruples them to the 380 GHz region (also enabling a wider frequency spread)
- The doublers needed for this are all developed, proven, and in hand
- For best performance, "Option B" needs the CMOS oscillators to have a finer amplitude tuning capability, so revised oscillators are in development

SWITCH transmitter detailed block diagram

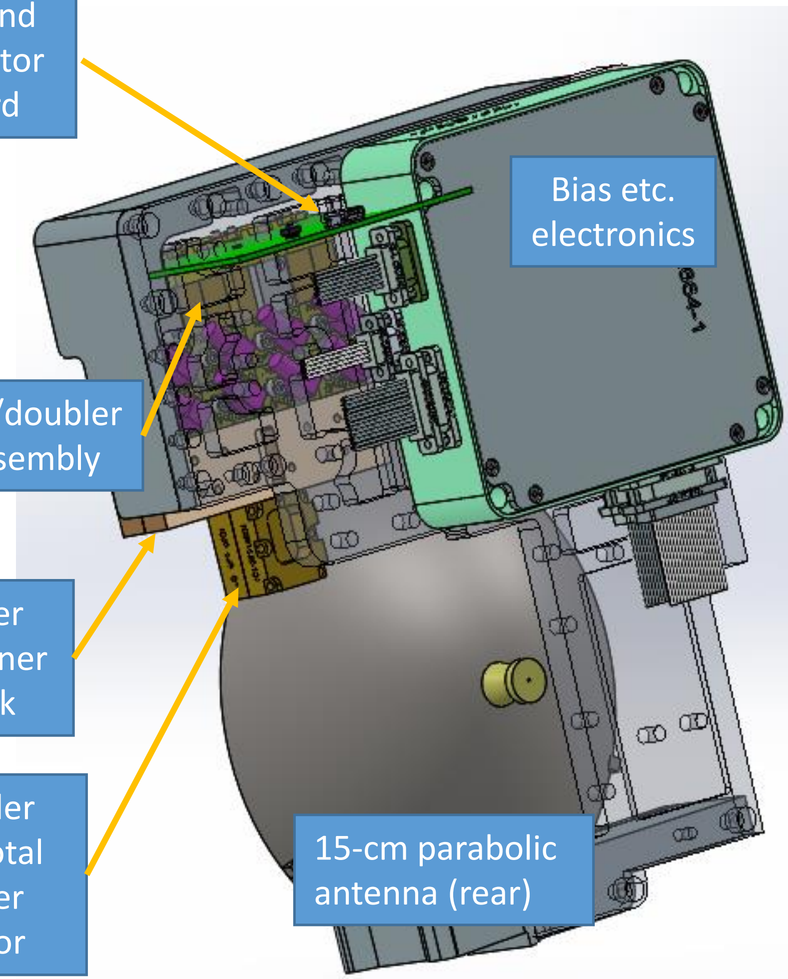


- All the above systems fit within a ~3U CubeSat form factor
  - Leaving an additional ~3U for the spacecraft

SWITCH transmitter design

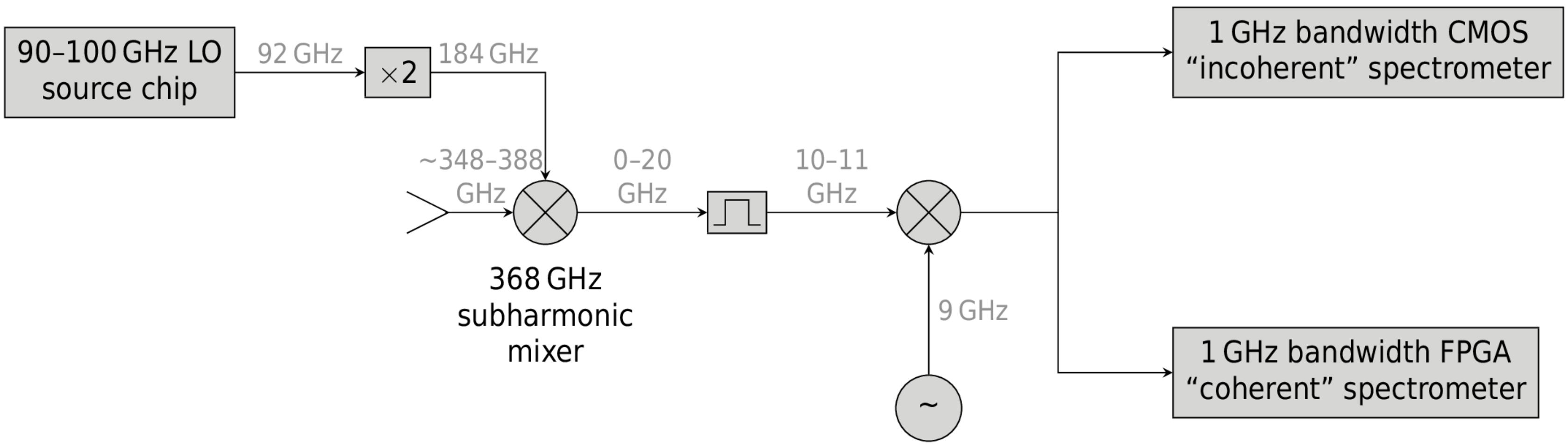


Sketch of core components of SWITCH transmitter assembly



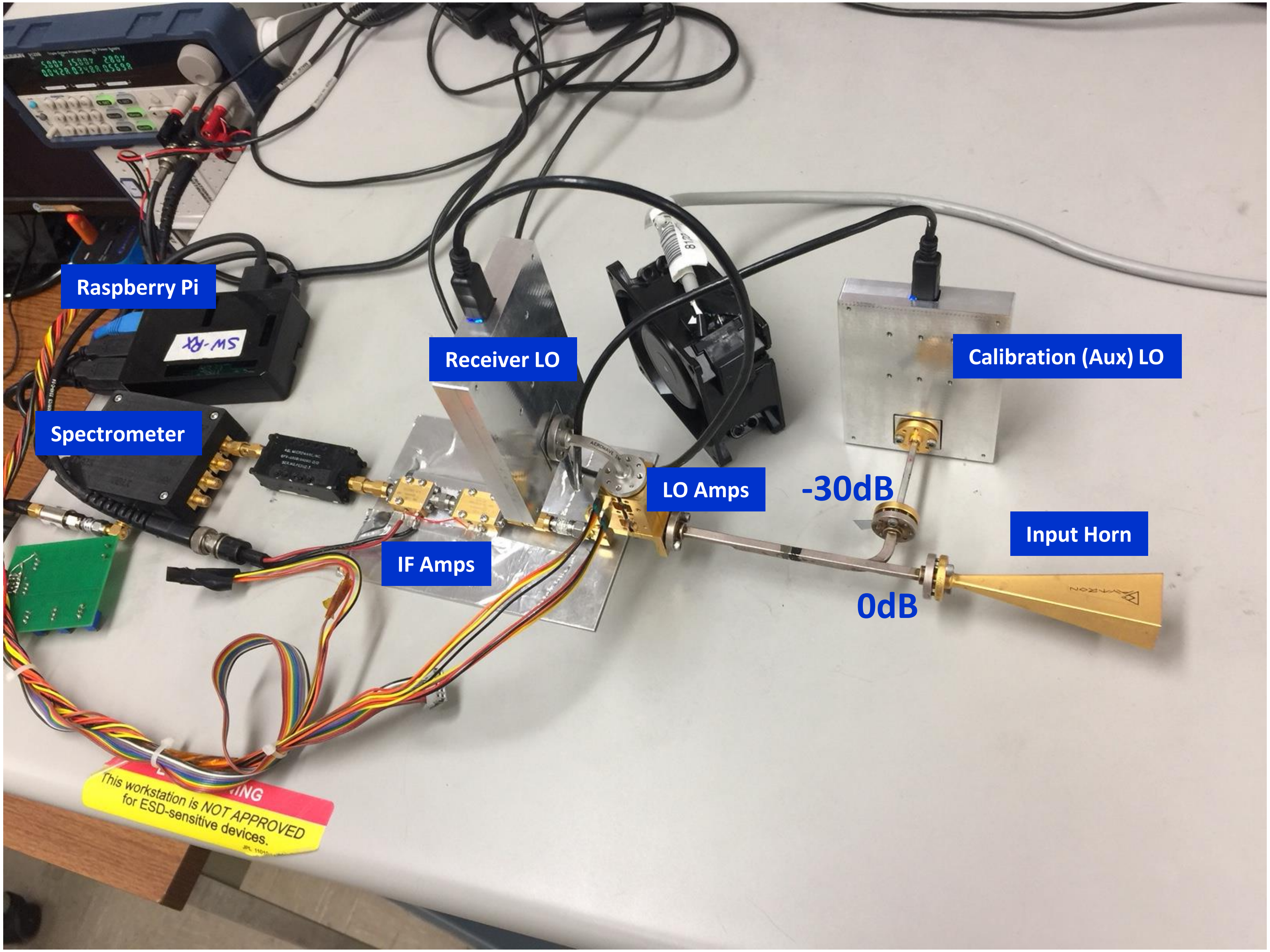
SWITCH transmitter assembly components in ~3U of 6U CubeSat

SWITCH receiver approach

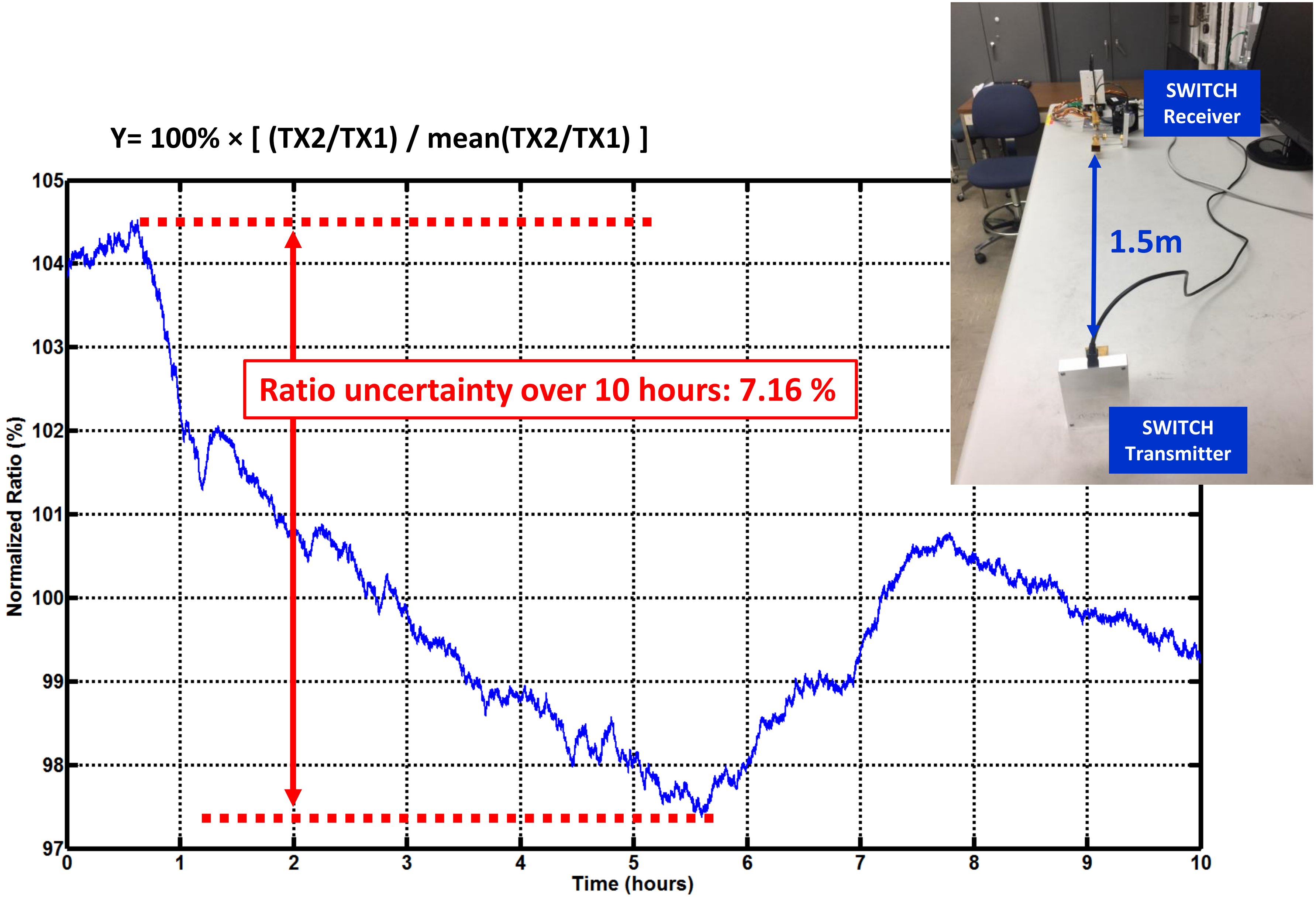


- The SWITCH receiver utilizes the same LO source chip as the transmitter
- This is followed by a doubler that drives a subharmonic Schottky mixer based on well-established designs for nearby frequencies
- We will employ two spectrometer approaches
- The first is a conventional CMOS digital spectrometer including an integrated ADC with a Hanning window and an FFT (an “incoherent” approach)
- The second employs a “coherent” design that includes a set of Digital Downconverters and a frequency tracking system to lock on to each tone
  - This will be developed in an FPGA
- The goal is to fit the entire receiver system into 3U of a 6U CubeSat form factor

SWITCH W-band (90–100 GHz) mock up – Receiver



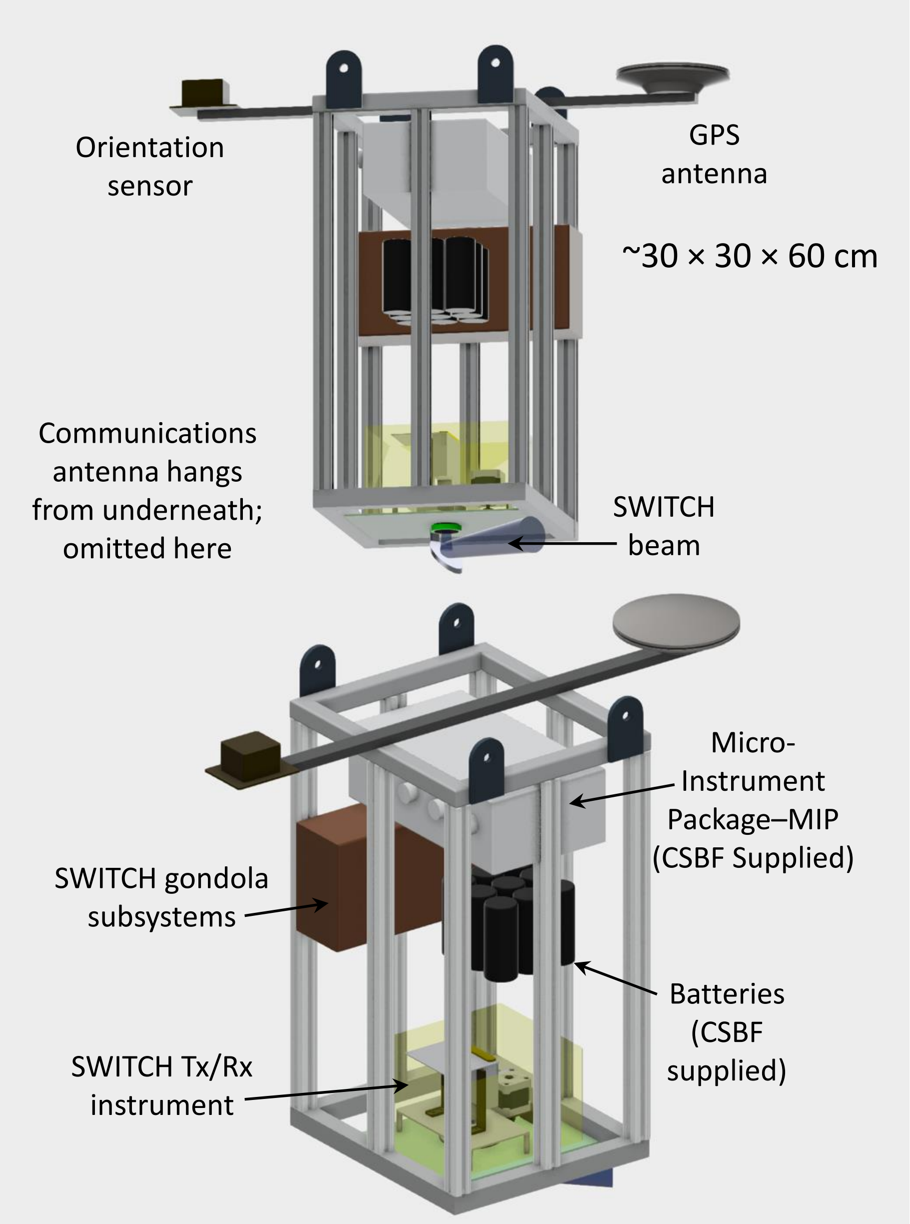
SWITCH W-band mock up – Full setup and findings



Approach to field testing and demonstrating TRL-6

- Demonstrating technology readiness for the SWITCH measurement concept in a “relevant” environment is not a simple undertaking
- The choice of spectral region has been optimized for measuring long paths through the thin and arid air around 12 – 18 km altitude
- Atmospheric absorption increases dramatically at lower altitudes
  - This limits ground-to-ground testing to ~1 km path lengths
  - It also precludes meaningful air-to-ground or ground-to-air testing
- Aircraft-to-aircraft testing is a possibility. However:
  - Major work would be needed to develop a complex and costly gimbal system that does not, in itself, advance the spaceborne SWITCH concept
  - Plus, getting simultaneous access to two high-altitude aircraft is a schedule and cost challenge
- The most feasible approach is to use a pair of high-altitude balloons
  - However, the altitude region SWITCH targets impinges on populated commercial air routes
  - Thus, any balloons must fly above those levels, reducing the water vapor line width to the degree that we will effectively have one “on line” tone and three “off line” ones
  - A ~50 km path length will be needed to accomplish useful levels of attenuation

Balloon to Balloon testing plans



- We are planning to install the SWITCH transmitter and receiver in a pair of otherwise identical small (<1 m^3) gondolas
- For the balloon-to-balloon configuration, we will transmit and receive a circularly polarized signal, enabling us to simply steer a single reflector
- The gondola will include a pointing sensor / control system to ensure that the transmitter and receiver mirrors point to each other
- Each gondola will be fed with near-real-time information on the location of the other
- This design also allows for more “relevant” ground-based testing of the balloon-to-balloon configuration

Future plans and summary

- The SWITCH measurement concept provides unprecedented resolution for observations of water vapor in the upper troposphere and lower stratosphere
- Our current project is developing the needed receiver and transmitter systems and testing them in ground-to-ground and balloon-to-balloon configurations
  - Fall 2018: Subsystem testing and instrument integration
  - January 2019: Ground-based testing
  - September 2019: Balloon-borne testing
- Our goal is to have the SWITCH system ready to propose for space flight at the end of this project
- An additional possibility is to combine in the SWITCH receiver satellite both the capability to perform the active “SWITCH” measurements and a separate passive limb-scanning receiver/spectrometer system for making “Continuity MLS” observations
  - These could share the same antenna (with the SWITCH receiver viewing a smaller portion of it to enable simultaneous viewing of all the transmitters)
  - This would enable us to combine “new science” and “continuity” in the same mission concept
- Many thanks to the NASA Earth Science Technology Office for continued support