NASA ESTO Microwave Technology Community Forum

March 17, 2016

EDT/PDT:	
11:00/08:00	Welcome/Overview of ESTO Investment Strategy Update (A. Valinia, NASA/ESTO)
11:20/08:20	State-of-the-Art and Future Requirements in Radar (F. Kantrowitz, Aerospace)
12:20/09:20	State-of-the-Art and Future Requirements in Microwave Radiometry (D. Kunkee, Aerospace)
13:20/10:20	*Break*
13:35/10:35	Data and Information Processing Future Requirements (A. Chandler, Aerospace)
14:15/11:15	Emerging Technologies and Trends (D. Kunkee, Aerospace)
15:00/12:00	Additional Input from Workshop Participants (All)
16:00/13:00	*Adjourn*

WELCOME!

<u>Before we begin, a few guidelines….</u>

- Please MUTE your microphones
- Please do not interrupt presentations in progress
- Please send questions via WebEx to the moderator: David Mayo (under the WebEx "Chat" feature). The moderator will pass the questions to the presenter, and they will be addressed during the Q&A. You will either receive a verbal response after the presentation or a written response (if we are time constrained).

Thank You!

Overview of NASA ESTO Microwave Remote Sensing Investment Strategy Update

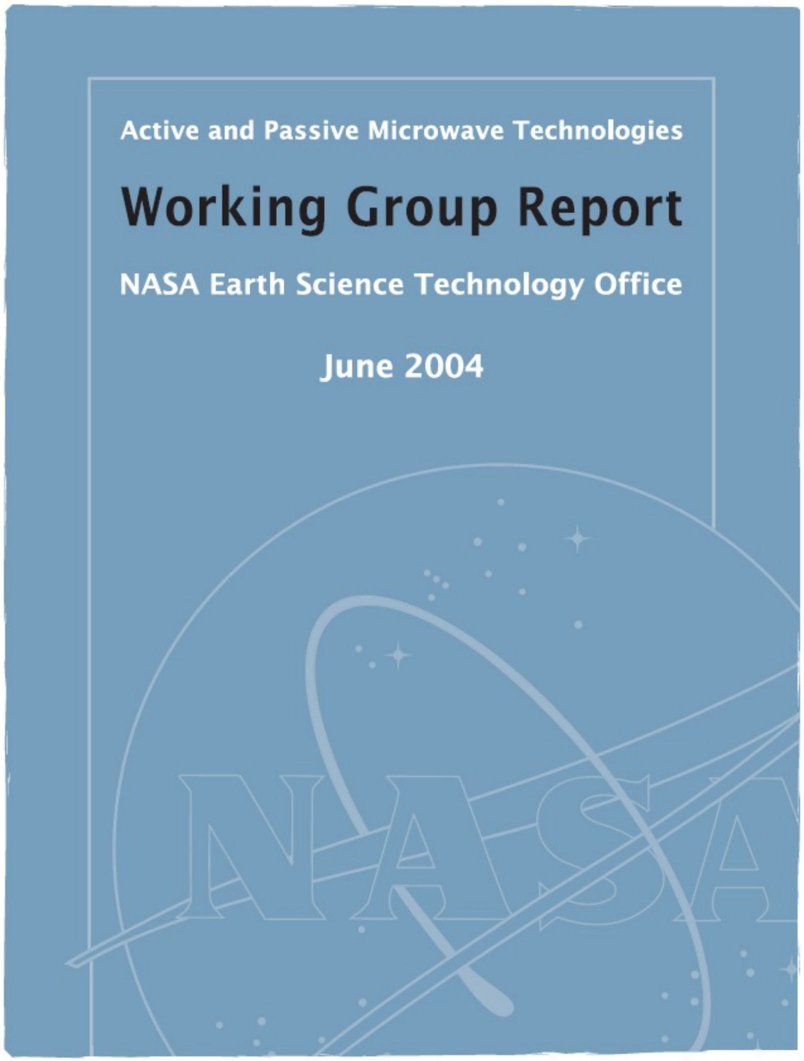
Purpose of the ESTO 2016 Microwave Strategy Update

- The last ESTO Microwave investment strategy is more than a decade old. State of the art has progressed and new areas have been entering the scene (e.g. miniaturized instruments, multi-frequencies)

- Update strategy by identifying and summarizing key technology requirements and performance parameters based on measurement themes: Atmospheric composition, Carbon & Ecosystems, Climate Variability & Change, Earth Surface & Interior, Water & Energy Cycle, Weather

- Opportunity for community to give input and play a role in shaping ESTO's future investment strategy

2004 Microwave Technologies Strategy


Active and Passive Microwave Technologies

Working Group Report

NASA Earth Science Technology Office

June 2004

NRC Decadal Survey - 2007

ESTO IIP Call – 2004

ESTO ACT Call - 2005

ESTO AIST Call – 2004

http://esto.nasa.gov/files/MWGReport2004.pdf

How will the final report be used?

- Use the input for upcoming ESTO AOs to inform ESTO's investment strategy
- Inform the Decadal Survey on the status of technology maturity
- Seek partnership opportunities with other agencies, industry, academia
- Identify emerging new technology trends and help infuse them into existing and future concepts

Microwave Study Core Team

- Azita Valinia – NASA/ESTO Study Lead
- Dave Kunkee – Aerospace Lead and Radiometer SME
- Frank Kantrowitz – Aerospace Radar SME
- Adam Chandler – Aerospace Data Processing Systems SME
- David Mayo – Aerospace Coordinator
- Jason Hyon – JPL Lead
- Terry Doiron – GSFC Lead

Process & Timeline

- Two 1-day workshops
  - JPL, GSFC (70 participants)
- Community Forum scheduled for March 17 (Virtual)

Today, the Core Microwave Study Team will brief Forum participants on how they have integrated inputs so far, and the emerging findings and investment strategy. Feedback and additional input welcome before finalizing the investment strategy.

https://esto.nasa.gov/MicrowaveStrategies/

Questions?

NASA ESTO Microwave Technology Community Forum

March 17, 2016

EDT/PDT:	
11:00/08:00	Welcome/Overview of ESTO Investment Strategy Update (A. Valinia, NASA/ESTO)
11:20/08:20	State-of-the-Art and Future Requirements in Radar (F. Kantrowitz, Aerospace)
12:20/09:20	State-of-the-Art and Future Requirements in Microwave Radiometry (D. Kunkee, Aerospace)
13:20/10:20	*Break*
13:35/10:35	Data and Information Processing Future Requirements (A. Chandler, Aerospace)
14:15/11:15	Emerging Technologies and Trends (D. Kunkee, Aerospace)
15:00/12:00	Additional Input from Workshop Participants (All)
16:00/13:00	*Adjourn*

NASA ESTO Microwave Technology

Status Evaluation

Radar Electronics & Antennas

Technologies Assessment

Contents

- **Summary of radar electronics & antennas technology needs**
  - *From 2007 decadal survey*
    - **Extended Ocean Vector Winds Mission (XOVWM) – C, Ku-bands**
    - **Surface Water and Ocean Topography (SWOT) – Ka-band (formerly Ku)**
    - **Aerosol Cloud Ecosystem (ACE) – W, Ka-bands**
    - **Snow and Cold Land Processes (SCLP) – X, Ku-bands**
    - **NASA ISRO SAR (NISAR) (formerly DESDynI Radar) – L-band**
    - **Soil Moisture Active Passive (SMAP) – L-band**
  - *Other measurement concepts*
    - **GEO weather radar (prior technology development at Ka band)**
    - **Cloud + precipitation processes: Ku, Ka, W-bands, Doppler, scanning**
    - **Dual L-, P-bands – deep soil moisture**
    - **SoOp systems – ocean wind vector, RFI detection**
    - **Humidity, temperature and pressure active profilers: V- and G-bands**
    - **GEO based systems – earthquake, hazard warning**
    - **Surface winds and currents: Doppler scatterometer, ATI**
    - **Compact cloud and precipitation radars for cubesats and smallsats**
    - **Subsurface (ice, aquifers, etc.): UHF to P-band “radar sounders”**
    - **Biomass structure : 3D SAR & InSAR architectures, tomography.**
- **Overview of technology status and development needs**
- **Conclusions and Recommendations**
- **Q&A**

Radar Assessment for the 2007 Tiered Decadal Survey Measurements

Capability Gap	Measurements	TRL	"Greatest Challenge" TRL
Ka-band phased array	Water surface topography (SWOT)	6	High phase stability Ka-band electronics
Ka, W-band scanning	Aerosol, cloud (ACE)	4	Closely spaced multi-band active feed array
X-, Ku-band feed array	Snow Cover (SCLP)	5	Multi-band feed
None	Soil Moisture (SMAP)	9	N/A
None	Surface deformation, ice (NISAR, formerly DESDynI radar)	6	System integration & test
High efficiency solid state amplifiers	Ocean wind vector (XOVWM)	5	Dual-band single instrument

Technology Needs for Future Measurements

Capability Gap	Measurement	TRL (Respondents)	"Greatest Challenge" TRL
Very large antennas	weather radar, hazard monitoring	2-9	Mass, deployment, highest frequency band
G-band technology	Humidity profiles	2-4	Transmit power generation
SoOp technology	Ocean wind vector, soil moisture, RFI detection for radiometers	3	Wideband tunable receiver
CubeSat / SmallSat radar technology	Precipitation, other	2-5	Antenna size, thermal. Power and data rate
Fully integrated single-chip MMIC T/R modules	All	3-5	Efficiency, T/R isolation
Improved High Power Amplifiers for high frequencies (Ka-,W-, G-bands)	Cloud profiles, rain droplet size, humidity profiles, atmospheric gases	2-6	Power supply reduced mass and size; improved efficiency; improved maximum RF power
Space-qualified, high bandwidth & nbits, integrated digital subsystems	All	4-9	Reduce risk and perception of risk going from non-space to space applications.

General Observations

- 2004 report radar electronics & antennas technology areas:
  - **Antenna Structure and electronics**
    - High Efficiency T/R modules
    - Light Weight Phased Array
    - Multiple Frequency Antenna/Multiple Feeds
    - Phased Array Feed for Reflector-type Antenna
    - High Efficiency Reflectarray
    - Large Deployable Rotating Reflector
    - Adaptive waveform sensing and correction technology
    - RF power, control, signal distribution
  - **Radar Electronics**
    - High power amplifiers
    - Waveform generators
    - A/D converters

General Observations

- Changes in 2016 Report
  - **Drop**
    - RF power, control, signal distribution for phased arrays
    - Large Deployable Rotating Reflector
  - **Add**
    - G-band technology
    - SoOp technology
    - CubeSat / SmallSat technology
    - Digital signal generation, beamforming & receiver electronics

Technology Areas 2016

Technical Area	2004 Report	2016 Report	Rationale
T/R modules	X	X	Key component for virtually all measurements
MMIC Devices	X	X	Mass and size reduction
High Power Amplifiers	X	X	Enabling for high frequency measurements
RF power, control, signal distribution	X	Drop	Mature
Waveform generators	X	X	Space qualify advanced waveform generators
Rotating Reflectors	X	Drop	Mature
ADCs for DBF	X	X	Reduce mass & power
Membrane antennas	X	X	Potential for array mass reduction
Adaptive waveform sensing	X	X	Potential for array mass reduction
SoOp		X	New measurement area
CubeSats / SmallSats		X	New measurement area
G-band technology		X	New measurement area
Digital signal generation, beamforming & receiver		X	Mass & power reduction

Specific Observations: Radar Electronics & Antennas

- L-, C-, X-band technology is mature
  - SMAP, NISAR, RadarSat II, TerraSAR-X
  - Future development should focus on technologies that will reduce cost for follow-on systems

- Many technology needs are related to phased array antennas or array feeds for reflectors
  - Array-fed reflectors do not all benefit from smaller/lighter T/R modules
    - Number of modules is smaller
    - Heat dissipation better for larger modules
    - Exception: multi-band array feeds
  - Single-chip MMIC based T/R modules at all frequencies
  - T/R module transmit efficiency, noise figure, T/R isolation
  - Line feed for parabolic cylinder reflector
    - Enables 1D electronic scanning for cloud / precipitation measurements
  - Digital beam forming for P-band phased array

Specific Observations: Radar Electronics & Antennas

- Dual/multi-band technology enables many measurements
  - Common antenna, electronics may reduce cost

- High structure mass limits practical use of phased arrays
  - Lightweight, small T/R modules do not solve problem
  - Use of phased arrays will require development of lightweight structures
    - Membranes, meshes, shape memory polymers
      - Thermal control
      - Power distribution
      - Small lightweight T/R modules to enable roll/fold up
    - Adaptive wavefront sensing for non-rigid structures
      - Computationally intensive for high frequencies

Specific Observations: Radar Electronics & Antennas

- Synergistic DoD Contractor development
  - *DARPA Innovative Space Based Radar Antenna Technology (ISAT) – Program had goal of developing 300 m long electronically steerable antenna for MEO based X-band Ground Moving Target Indication (GMTI) radar*
    - *Most work focused on development of large deployable structures*
    - *Boeing, Northrop Grumman, Lockheed Martin were prime contractors*
    - *Raytheon, Harris were radar payload subs*
    - *Program funded from 2002 – 2007*
    - *Ref: J. Guerci, E. Jaska, IEEE International Symposium on Phased Array Systems and Technology, pp 45 – 51,14-17Oct2003.*
  - DoD phased array technology
    - *Many airborne radars using phased array antennas*
    - *DARPA Arrays at Commercial Timescale (ACT) program*

Challenges

- Transmit power at high frequencies
  - *EIKAs – reducing high voltage power supply mass, improving efficiency*
  - *Improving SSPA efficiency*

- Dual/multi-band feeds/antennas that enable the same coverage at different bands
  - *Common antenna, electronics covering dual band*
    - *E.g. Harris current sheet array feed*

- Understanding technologies that enable new measurements
  - *E.g. multiple look angles, tomography*

- Understanding measurement limitations for emerging radar technologies
  - *Signal-of-Opportunity based bistatics*
  - *CubeSats, SmallSats*

Challenges

- Significant SWAP reduction
  - *Most system concepts are high SWAP and very expensive*
  - *Planned technology development will result in small, incremental improvements*
    - *Unlikely to significantly reduce cost*
    - *Possible exception: cubesat-inspired new architectures have potential to significantly reduce mass and number of parts, subsystems and interfaces.*

- New technology insertion
  - *Lightweight array structures may enable use of electronically scanning phased arrays instead of reflectors*
  - *Need to understand benefit to measurement*

Radar Technology Needs Summary

Band	VHF/P	L	C	X	Ku	Ka	W	G
Measurement	soil moisture		ocean wind vector		surface water topo		humidity	
	ice			snow		hydrometeor		
	biomass	surface deformation				weather		
					precipitation			
						clouds		
Antenna	large lightweight structures				dual/multi band array feed			
	single-chip MMIC T/R module				single-chip MMIC T/R module			
	DBF						lightweight reflectors	
Amplifier						HPAs – lighter, smaller, higher efficiency		
					GaN SSPA for higher efficiency			
Payload Electronics	space-qualified, high bandwidth & nbits, integrated digital subsystems							
System	explore measurement enhancements from using lightweight phased arrays							
	applying cubesat technology to larger sats							
	SoOp systems							

Preliminary Conclusions and Recommendations

Conclusions

- Dual/multi-band technology enables several measurement scenarios and has not received as much focus as it should
- Many technology needs are related to array feeds for reflectors
- Development of higher power, space qualified high power amplifiers and T/R module transmit amplifiers are most important at higher frequencies (Ka, W, G-bands)
- Signals-of-Opportunity and CubeSats both present new opportunities although specific measurement scenarios have not been fully determined
- MMIC based T/R modules have most value when there is a need for smaller, lighter modules
- Development of digital technology will enable mass & power reduction
- Ka-band has largest number of measurements
- Up-front system design trades are essential for determining technology needs

Preliminary Conclusions and Recommendations

Recommendations

- Develop a better understanding of the benefit of specific technology needs
  - Focus on technology development that will lead to significant cost reduction
  - Where technology development will enhance performance, quantify the improvement
- Develop measurement concepts for SoOp and cubesats to better understand their value
- Develop integrated dual/multi-band technology which potentially can reduce cost

Questions & Comments

NASA ESTO Microwave Technology Community Forum

March 17, 2016

EDT/PDT:	
11:00/08:00	Welcome/Overview of ESTO Investment Strategy Update (A. Valinia, NASA/ESTO)
11:20/08:20	State-of-the-Art and Future Requirements in Radar (F. Kantrowitz, Aerospace)
12:20/09:20	State-of-the-Art and Future Requirements in Microwave Radiometry (D. Kunkee, Aerospace)
13:20/10:20	*Break*
13:35/10:35	Data and Information Processing Future Requirements (A. Chandler, Aerospace)
14:15/11:15	Emerging Technologies and Trends (D. Kunkee, Aerospace)
15:00/12:00	Additional Input from Workshop Participants (All)
16:00/13:00	*Adjourn*

NASA ESTO Microwave Technology Status Evaluation

Radiometer and Antenna Technologies Assessment

Contents

Passive Microwave Assessment for the 2007 Tiered Decadal Survey Measurements

Capability Gap	Measurements	TRL	"Greatest Challenge" TRL
High-frequency low power Radiometers	Wet Path (SWOT)	6	High performance low SWaP radiometers to ~250-GHz
Broadband Spectrometer	UA Chemistry (GACM)	5	High performance RF Front-ends at 500 – 600 GHz
None	Snow Cover (SCLP)	7 - 9	N/A
None	Soil Moisture (SMAP)	7 - 9	N/A
High spatial and temporal resolution sounding - GEO	Precipitation Atmospheric Temperature/ Humidity (PATH)	6	V-/G-band GeoSTAR system
High spatial and temporal resolution sounding - LEO	PATH	5	Low Cost Microwave spectrometers on CubeSats

Enabling Technologies for New Measurement Concepts

Capability Gap	Measurement Concept	TRL	"Greatest Challenge" TRL
Concurrent Radar and Radiometer measurements; wide range of radio frequencies	Precipitation, Root Zone SM, SSS, Air-Sea Flux/Sea Ice and Ocean Altimetry measurements	4	Integrated Radiometer & Radar transmitter (P- L- S-band; K-Ka-band; Ka-G-band)
Polarimetric Radiometry from L- to SMMW	Ocean Surface Winds; high spatial resolution phenomena	3 - 7	Microwave polarimetry at W-band and above (lower TRL for higher frequencies)
Low SWaP-C G-band heterodyne receivers	High repeat atmospheric water vapor and temperature profiling	6	Low Power: <50mW; Low Mass: 100g; low power LOs
P-band radar/radiometry with additional bands	Root-Zone Soil Moisture	4	Wide bands at low frequencies (P-band); spectrum sharing technology
Super-heterodyne receivers; 500 – 600 GHz + G-band (SWaP-C)	Trace gasses; atmospheric water and temperature profile	3	100mW; 200g; 300 K T_{sys} at ~80 K
SWaP-C of G-band WV profiling radiometers	Tropospheric winds from repeat pass WV radiometry	5	Technique needs to be proven; requirements for low-cost sensor still TBD (Technology TRL is high)

Enabling Technologies for New Measurement Concepts

Capability Gap	Measurement Concept	TRL	"Greatest Challenge" TRL
Dual polarized radiometers operating at 89 - 650 GHz;	Cloud Ice, tropospheric water characterization	2 – 5	Low power, 0.5W/size to fit in a focal plane/feed array; low BW (2%) filters; Lower TRL for higher frequencies
Low cost atmospheric sounding for 'high volume' use in small platforms	Clouds and precipitation processes – high temporal	4	300K T_{rec}; up to 183-GHz; <50mW; <100g
2m class deployable antenna	Improved HSR for traditional measurements from low cost/ small platforms	3	Performance to ~600 GHz; stowed volume ~ 2.5U
Broadband well-calibrated frequency agile radiometer	Imaging radiometer coverage in environments with increasing RFI	4	25 kHz band segments from 1 – 50 GHz
P- to K-band feed array for large reflector	Root Zone Soil Moisture	5	Radiometer FE to fit within a specialized feed array
Direct SI traceability; Distributed Cal for STAR; Calibration of UAV radiometers	Radiometer Calibration	4	Blackbody standards & analysis; Stability of distributed Cal; (SM) System-based approach to Cal;

Enabling Technologies for New Measurement Concepts

Capability Gap	Measurement Concept	TRL	"Greatest Challenge" TRL
Broadband/Multiband FPA feed technologies to support ~7m aperture antennas	Spatial Resolution Improvements to OSW, Cloud Liquid, Precipitation, Integrated Water, Snow Cover etc.	4	10-1 band feeds with high beam efficiency and surface factor to W-band;
Large deployable antenna (e.g. D >= 10m and f =< 40 GHz)	Ultra-high spatial resolution for imaging below 40 GHz	3 - 5	>90% beam efficiency; mods to existing commercial antennas
SMMW Receiver Technology: Instrument front-ends (including LNAs); filters; detectors; calibration noise sources and switches; isolators	Cost effective high temporal sampling of precipitation, clouds, and ice	2 - 5	5dB NF from 200 – 1000 GHz (High TRL); filters to allow SSB operation at 10% BW (Low TRL); Direct detection at <100K added noise temperature (Mid TRL)

Background

- **The 2004 MWG Report Contains 8 technology Areas in Radiometer Electronics:**
  - *High Frequency Electronics*
  - *Miniaturized Radiometer Technologies*
  - *Analog RFI Mitigation*
  - *Correlation Radiometer Calibration Sub-system*
  - *On-board RF Signal distribution*
  - *3 or 4 Stokes' – Polarimetric Receiver Design*
  - *Ultra-stable Low-Loss Radiometers*
  - *Combined Passive / Active System Design*

- **Areas changed in 2016 report**
  - Expanded role of combined passive / active designs and calibration
    - Several applications for combined technologies and over a broad range of frequencies
  - Expanded RFI mitigation to include digital technologies
    - Added spectrum sharing and greatly improved performance of digital spectroscopy and Kurtosis
    - Added broad-band radiometer capability with adjustable band segments and tunable notches
    - RFI mitigation capability expected to become increasing important in future measurements
  - Added Cryo-coolers
    - Compact, low power cryo-coolers for improved performance in subMMW region

Background

- **The 2004 MWG Report Contains 7 technology Areas in Antennas Related to Radiometers:**
  - *Low Profile Lightweight Array Feeds*
  - *Millimeter Wave Scanning Antenna*
  - *Mechanically Scanning Aperture for Millimeter Wave*
  - *Rotating Large Aperture for Low Frequency*
  - *Torus with Electronically Scanning Feed Array*
  - *2-D STAR with Receiver Elements*
  - *2-D STAR with Membrane WG Technology*
- **Capability Thresholds**
  - *10 km L-band; 5 km K-band measurements from LEO;*
- **Areas changed in 2016 report**
  - Focused 2-D STAR concepts on Geo-STAR concept
    - No discussion of membrane WG technology
  - Larger antennas for traditional frequency bands
    - Desire for improved Horizontal Spatial Resolution
  - Additional focus on multi-frequency and active/passive sensor integration
    - Quantitative requirements TBD

Technology Areas 2016

Technical Area	2004	2016	Rationale
High Frequency Radiometers	X	**X**	Core technology enabling measurements from smaller low cost platforms
Miniaturized and multi-frequency radiometers	X	**X**	Core technology technology for measurements requiring multiple frequencies or combination with Radar
RFI Mitigation (S/W & H/W)	X	**X**	Increasingly important to maintain measurements
Radiometer Calibration	X	**X**	Expanded to include SI-standard and UAV-based sensors
Polarimeters (L- W-band)	X	**X**	OSWV and Cloud Ice;
Combined Active/Passive FEs	X	**X**	Core technology for many measurements
2m deployable (<350 GHz)	-	**X**	Crosscutting – improvements in SWaP-C; HSR
6m class antennas (<100 GHz)	X	**X**	Crosscutting – enables improvements to HSR
10m class antennas (<40 GHz)	X	**X**	Crosscutting – enables improvements to HSR
Cryocoolers	-	**X**	Cloud Ice / high frequency radiometer performance

Observations

- **Need for radiometric measurements > 200-GHz to 1000-GHz will drive LNA and radiometer front-end technology developments**
  - *Ice Cloud characterization mission require higher frequency observations and shorter revisit times driving lower costs and implementation on multiple (small) platforms*
  - *Low SWaP-C drives investigation into direct detection approaches to 1000 GHz*
  - *Alternate approaches involve heterodyne designs with concentration on low power LOs*
  - *Better performance will benefit many areas including atmospheric and water vapor sounding*
- **Measurements requiring multi-frequencies and/or multi sensors drive many cross-cutting technology investments**
  - *State-of-the-Art is separate receiver chains and use of multiplexers*
  - *Approach to achieve adequate RF isolation*
  - *Packaging multi-frequency feed structures and RF front-ends*
- **RFI Mitigation**
  - *Continues to drive technology investment due to increasing impact to passive measurements*
  - *Better algorithms to achieve better detection and frequency agile hardware to perform measurements where no anthropogenic sources are detected or exist*

Observations (cont.)

- **Antennas: Larger or deployable apertures for traditional operating frequencies**
  - *Deployable antennas to overcome diffraction limit from systems required to fit within cubesat dimensions (up to 2m diameter aperture from 2.5U stowed configuration)*
  - *6m class antennas with higher operating frequencies (up to 100 GHz)*
  - *10m diameter or larger antennas using SMAP frequencies up to 40 GHz*
- **Antennas: Shared aperture using multi-frequencies and/or multi-sensors (Active, Passive and SoOp)**
  - *Focal plane array configurations accommodating multiple sensor front-ends*
  - *Multi-frequency feeds (e.g. cylindrical parabola)*
- **Polarimetry**
  - *Polarimetric radiometers operating above Ka-band (up to submillimeter wave frequencies)*
- **Thinned aperture radiometers**
  - *2D STAR sensors to support PATH is still relevant (TRL 6) and both competes with and complements LEO constellation approach*

Technology Needs: High Frequency Radiometers

Measure-ment(s)	Technology	State of the Art	Requirements	Development Need
Cloud Ice; Precipitation	High frequency receiver front-ends operating from 89-GHz up to >800-GHz	183-GHz LNAs @ 500 K noise temperature; frequency; down conversion; DSB configuration with filtering to achieve 3-5 separate offsets from 183-GHz line. Passive front-ends above ~200-GHz and noise temperature >>500 K operating at room temperature	300K noise temperature at room temp @183 GHz; Power <0.05W; Mass<100g	• Reduce mass, volume and power requirements of high frequency radiometers • Low Power LOs • Filtering at primary frequency of operation • Wideband receivers (multi-band backends) • Sufficiently small enough to fit within a single focal plan
Atmospheric Chemistry	High frequency receiver front-ends operating from 500- to 600-GHz	Passive front-ends above ~200-GHz and noise temperature >>500 K operating at room temperature	MMIC-based superheterodyne integrated receivers: 300K @ 20K, 500 GHz Power: <0.1W; Mass<200g	• Continued improvement of performance and f_{MAX} for high frequency InP LNAs • Performance under cryo-cooling may become an option • Low NF and noise stability are primary metrics

Technology Needs: Integrated Radiometers with Radar Transmitters and Receivers

Measure-ment(s)	Technology	State of the Art	Requirements	Development Need
Precipitation	*Under review*	High power switching; frequency multiplexers with individual receiver chains	Instrument Front-end (small SWaP); 1 unit on a small platform operating with many platforms: Power: 10 – 30W; efficiency 40%	Single unit on a small platform
Root Zone Soil moisture/ SSS/ Air-Sea-Flux/ Sea Ice	*Under review*	High power switching; frequency multiplexers with individual receiver chains	Instrument Front-end; stable internal calibration	Coexistence with Radar unit; single instrument front-end .
Ocean Surface Winds/ Altimetry	*Under review*	High power switching; frequency multiplexers with individual receiver chains	*Still under review*	Integrated polarimeter and radar receivers

Technology Needs: RFI Mitigation

Measurement(s)	Technology	State of the Art	Requirements	Development Need
Root Zone Soil Moisture	Broadband tunable notch filter; spectrum sharing technology	*Still in review*	Tunable from ~400-MHz to 2-GHz; Low loss; high selectivity	*Still in review*
Imagery over populated areas	Ultra Broadband Digital Spectrometer	3 GHz BW with CMOS 65-nm technology;	20- to 50-GHz BW; Improvements in spectral resolution; mitigation techniques	*Still in review*

Technology Needs: Radiometer Calibration

Measurement(s)	Technology	State of the Art	Requirements	Development Need
Imagery; Atmospheric Temperature Sounding;	SI Traceability (through the antenna)	SI-traceable blackbody temperature sensors – misses largest uncertainty	Techniques developed	Black body standards, traceability techniques
Atmospheric Temperature and Humidity Profiles	Distributed calibration techniques for STAR	*Under review*	Instrument front-end; stable internal calibration	*Still under review (Soil Moisture concepts)*
Imagery; high revist/ regional measurements	Calibration of UAV radiometers	Sensor and platform unique artifacts / biases requiring reprocessing before integration/assimilation	Level 3 calibrated data with minimal or no unique application-specific / platform-specific reprocessing	Combine information about ambient environment to improve unattended airborne (vs. space-based) instrument calibration
Atmospheric Sounding; Cloud Ice	183-GHz and higher noise sources for internal calibration	W-band internal noise sources are beginning to be established	Calibration stability (TBD) ENR (TBD) Low loss RF switches	*Under review*

Technology Needs: Polarimetry

Measurement(s)	Technology	State of the Art	Requirements	Development Need
OSWV, Imaging (W-band), Cloud characteristics and EPBR	High performance stable polarimetric receivers W-band and above	K_a-band (WindSat)	Polarimetric radiometers with channel-to-channel calibration; matching dual-pol radiometers	High frequency polarimetric back-ends (analog) or wideband digital back-ends
Electronic Polarization Basis Rotation (EPBR)	Internal radiometric calibration performance at W-band and above	K_a-band (TRL 6)	Enable Electronic Polarization Basis Rotation for Conical scanners	Stable noise diodes at W-band to G-band and above

Technology Needs: 2m Class deployable antennas

Measurement(s)	Technology	State of the Art	Requirements	Development Need
Precipitation; clouds: L-band through 350 GHz (lower cost alternatives)	2m deployable antenna and feeds	1.5U stowed; 0.7m aperture deployed	Surface figure: W-band: full aperture; f<350-GHz: 1m diameter Stowed volume: 2.5U	Develop and demonstrate 2m deployable reflector;

Technology Needs: 6-7m class antennas and larger

Measurement(s)	Technology	State of the Art	Requirements	Development Need
Root Zone Soil Moisture/ SSS/ Air-Sea Flux/ Sea Ice	Broadband/ Multiband Focal Plane Array Feed Technologies for Large (e.g. >7m) Antennas	Single band and/or multiple feedhorns	10-1 band feeds (options); non-moving conical scan; P/ L/ S/ C-band; 40° ONA; Multi-angle may also be useful	Combined Radar/ Radiometer/ SoOp; Multi-purpose SDR; reconfigurable frequency agile systems
High resolution imagery to support Snow/ OSWV/ Precipitation & cloud amount	6-/10-GHz through 90 GHz, spatial resolution substantially better than AMSR-2. (e.g., 6-meter deployable)	2m class apertures for multi-frequency space-based radiometers	~6-m reflector radiometer antenna; spatial resolution substantially better than AMSR-2. (e.g., 6-meter deployable); array receivers to accommodate Nyquist sampling	6m deployable reflector with surface figure to support W-band

Technology Needs: STAR Instrument Systems

Measurement(s)	Technology	State of the Art	Requirements	Development Need
Atmospheric Sounding;	Analog/Digital Cross Correlator	TRL 6	1-GHz IF band; 250 uW/correlation; 256x256 inputs; 500 MHz BW	*Still in review*
Root Zone Soil Moisture and Sea Ice	Distributed Correlators operating at P/ L/ S/ and C-band	TRL 3	<100 MHz; limited baselines in distributed STAR systems	*Still in review*

Technology Needs Trades

	P- /S-band 400-MHz to 2-GHz	C- /W-band 6- to 90-GHz	W- /G-band 100- to 200-GHz	SMMW 300-GHz to 1-THz
Measurement	Root Zone SM; SSS;	OSWV; SST; Imagery Ocean Altimetry; IWV Atmospheric Sounding; Cloud Amount; SWE	Atmospheric Temperature and water vapor profiles	Cloud characterization; cloud Ice
Antennas/ Aperture	up to 10m aperture vs. distributed correlation systems	Up to 7m aperture(s); multi-band FPA; cylindrical / offset parabola; STAR at GEO	Deployable 2m dia from 2.5U stowed volume – various altitudes	Deployable up to 1m – various altitudes
Radiometer	RFI mitigation – tunable notches, broadband radiometers; frequency agile	Low SWaP-C radiometers integrate-able with Radar systems	Low SWaP-C radiometers; Low power LOs; Direct detection; filter technology	Low SWaP-C radiometers; low power LOs; direct detection; LNA performance
Platform	3-D ranging; formation flying; UAV	Reliable 5-yr cube-sat bus; UAV; imaging on demand (hurricanes/ storms);	Reliable 5yr cube-sat bus; power limitations;	Reliable 5yr cube-sat bus; power limitations;
IT/ Data processing	Multi-sensor processor: Passive/Active/SoOp	Small sat data transmission;	Small sat data transmission;	Small sat data transmission;

Radiometer Technology Needs Summary

Band	P	L	C	X	K	K_a	V	W	G	smmW
Measurement		Soil Moisture			Ocean Wind Vector					Atmospheric Comp
		Salinity			Snow Cover/Depth					Cloud Ice / Trop Proc
					Precipitation				Precipitation	
						Cloud Liquid		Cld lqd		
							Temp		Humidity	
Antenna Feeds and Reflectors					Integrated active/passive multi-band front-ends / FPAs					
							Deployable 2m class			
			(10m)		Large reflectors		(7m)			
Receiver Electronics				Miniaturization (Integration: Active / FPA)					Miniaturization (SWaP-C)	
									LP LO	Performance
Calibration		Distributed Correlators			UAV				Direct SI-Traceability	
System		Distributed Correlators					Correlators		Correlators	
		Formation flying / STAR				EPBR Polarimetry				
								Constellation Management		

Preliminary Conclusions and Recommendations

- **Improvements in high frequency radiometer RF performance and SWaP-C**
  - Needed for several measurements including Cloud and atmospheric boundary layer, precipitation processes
  - Improved radiometer components desired (LNA's, filters, detectors, isolators) for operation at higher frequencies
  - Cryo-coolers may help, but may not be most effective path to the performance improvements desired
- **Multi-frequency and multi-sensor shared aperture measurements will drive developments in antennas and radiometer electronics**
  - Integrated Radar/Radiometer hardware allowing radiometer to coexist with radar systems
  - Multi-frequency FPA array designs to enable technology trades in Root Zone SM
  - Multi frequency feed for cylindrical antennas
- **RFI mitigation techniques in hardware and software**
  - Spectrum sharing techniques (notch filter, effective RFI detection and mitigation) is of increasing priority for low band measurements and especially needed for Radiometers attempting root zone soil moisture at P-band
- **Deployable apertures could enable measurement scenarios from smaller satellite platforms**
  - Current capability: 0.7m from 1.5U; this capability may continue to improve but best value goal is not clear
  - Larger class of stowed volumes commensurate with dual ESPA ring launch opportunities are also important
  - 6 – 10 m diameter apertures desired for improving spatial resolution of existing 'operational' measurements
- **Additional developments needed to support distributed/ multi-sensor approaches to lower cost**
  - Small platform reliability /power availability / data handling
  - Large constellation management/ modelling (additional discussion in emerging technologies)

Questions & Comments

NASA ESTO Microwave Technology Community Forum

March 17, 2016

EDT/PDT:	
11:00/08:00	Welcome/Overview of ESTO Investment Strategy Update (A. Valinia, NASA/ESTO)
11:20/08:20	State-of-the-Art and Future Requirements in Radar (F. Kantrowitz, Aerospace)
12:20/09:20	State-of-the-Art and Future Requirements in Microwave Radiometry (D. Kunkee, Aerospace)
13:20/10:20	*Break*
13:35/10:35	Data and Information Processing Future Requirements (A. Chandler, Aerospace)
14:15/11:15	Emerging Technologies and Trends (D. Kunkee, Aerospace)
15:00/12:00	Additional Input from Workshop Participants (All)
16:00/13:00	*Adjourn*

NASA ESTO Microwave Technology Community Forum

March 17, 2016

EDT/PDT:	
11:00/08:00	Welcome/Overview of ESTO Investment Strategy Update (A. Valinia, NASA/ESTO)
11:20/08:20	State-of-the-Art and Future Requirements in Radar (F. Kantrowitz, Aerospace)
12:20/09:20	State-of-the-Art and Future Requirements in Microwave Radiometry (D. Kunkee, Aerospace)
13:20/10:20	*Break*
13:35/10:35	Data and Information Processing Future Requirements (A. Chandler, Aerospace)
14:15/11:15	Emerging Technologies and Trends (D. Kunkee, Aerospace)
15:00/12:00	Additional Input from Workshop Participants (All)
16:00/13:00	*Adjourn*

NASA ESTO Microwave Technology Status Evaluation:

Information Processing Technologies Assessment

Contents

- **Summary of information technology needs assessment for measurements from the 2007 decadal survey**
  - *Radar waveform generation (ACE)*
  - *Compression algorithms (GACM)*
  - *Modeling and simulation, RFI mitigation, retrieval algorithm development (ACE, GACM, SCLP, …)*
- **Summary of information technology needs for new measurement concepts**
  - *Spacecraft hardware (A/D, networking, data storage, processors)*
  - *Inter-spacecraft metrology and communication (formation control, aperture synthesis)*
  - *Adaptive tasking and coordination*
  - *Data compression and downlink*
  - *Ground data storage, processing, distribution*
- **Overview of information technology development needs**
  - *Onboard processing and data handling*
  - *Spacecraft control and communication*
  - *Ground processing*
  - *Algorithms/models*
- **Recommendations**
- **Q&A**

C&DH Assessment for 2007 Decadal Survey Measurement Recommendations

Capability Gap	Measurements	TRL
Waveform generation/ultra-low-range-sidelobe pulse compression	Clouds (ACE - radar)	5
OSSE; mission configuration and performance studies	Aerosols, Clouds (ACE)	2-5
Information-aware compression algorithms for downlink and RFI mitigation	Atmospheric composition (GACM)	3
Advanced 3D tomographic retrieval algorithms	Atmospheric composition (GACM)	3
Retrieval algorithms	Snow water equivalent, depth, wetness (SCLP)	3

Other decadal missions (XOVWM, SWOT, PATH, NISAR/DESDynI) reported no unmet data processing technology needs

Enabling Technologies for New Concepts

Capability	Concept (measurements)	TRL	Challenge
Onboard storage	Synoptic, multi-sensor, and/or data-intensive measurements (e.g. land deformation, topography, vegetation height/density,…)	4-5	Capacity, speed, SWAP
Onboard processors	Rad Hard By Design, 3D ICs (applicable to wide variety of measurements; e.g., tasking for storm observation, range compression for profiling)	3-5	Performance, SWAP, reusability
Onboard algorithms	Adaptive beam forming, adaptive tasking, formation control, RFI detection and mitigation, compressive sensing, data reduction, data compression (applicable to wide variety of measurements)	2-4	Development, implementation
Fast ADCs	Wide-bandwidth radiometry – digitize 20+ GHz, adaptively channelize to mitigate RFI (RFI mitigation, atmospheric composition)	4	Power, performance for radiometry
High-speed, high-res digital correlators / spectrometers	RFI mitigation over up to 20+ GHz bands (applicable to wide variety of measurements)	4-5	Large BW, # of channels, SWAP

Enabling Technologies for New Concepts

Capability	Concept (measurements)	TRL	Challenge
Advanced radar waveform generation	Frequency and/or phase diversity for multiple, simultaneous independent looks (e.g. clouds, precipitation, storms)	5	Implementation, space qualification
Affordable continuous coverage/high revisit rates	Constellations of smallsats (e.g. temperature, moisture, precipitation, wind vector in dynamic environments)	3	Coordination, calibration
Automated event-driven operation, low-latency retasking	Hierarchical collection methodologies, dynamic reallocation of resources based on detected events/features (e.g. temperature, moisture, precipitation, wind vector in dynamic environments)	3	Robust event detection; rapid coordination
Inter-spacecraft metrology for ~cm-level formation control	Increased use of smallsats; synthesize larger apertures using formation flying (e.g. root zone soil moisture, sea surface salinity, air-sea flux measurements)	2-4	Low-SWAP-C metrology solution
Fast external data links	Data sharing among satellites in formation (e.g. root zone soil moisture, sea surface salinity, air-sea flux measurements)	3	Low-SWAP-C

Enabling Technologies for New Concepts

Capability	Concept (measurements)	TRL	Challenge
Fast, reliable downlink	Increased data production – multiple payloads, smallsat constellations, data-intensive SARs, … (e.g. precipitation, root zone soil moisture, cloud processes, deformation, topography)	3-5	Space and ground infrastructure, laser COMMs, SWAP-C/ specialization for smallsats
Ground data management	Big Data – petabyte storage, persistent teraflops processing, data fusion, distribution (applicable to wide variety of measurements)	3	Interoperability, tool development, efficiency, cost
Modeling, simulation, processing algorithm development	Enable new instrument/constellation concepts, new measurements/products, new CONOPS (applicable to wide variety of measurements)	2-3	Standards, interfaces, reusability

General Observations

- **Certain capability gaps are better categorized as engineering issues than technology**
  - *Adapting existing technologies*
  - *Instrument-specific retrieval algorithm development*

- **Technology investment should have clear payoffs**
  - *Enable new science, measurement capabilities*
  - *Improve quality, efficiency, or effectiveness of existing capabilities*

- **Several concept themes emerged during JPL/GSFC workshops**
  - *Adaptive processing and tasking*
  - *Coordination of multiple spacecraft*
  - *Handling of large data volumes*

- **Majority of technology development needs can be placed into the following overarching areas:**
  - *Onboard processing*
  - *Spacecraft control & communication*
  - *Ground processing*
  - *Algorithms/models*

Onboard Processing – Applications

- **Optimize data collection**
  - *Adaptive beam forming*
  - *Adaptive channelization*
  - *Efficient spectrum utilization*
  - *RFI detection and mitigation*
  - *Accommodations for instrument health*

- **Enable adaptive tasking**
  - *Data reduction for feature/event detection*
  - *Automated event-driven tip-offs; coordinated retasking of same or other spacecraft*

- **Enable formation flying**
  - *Process metrology inputs to inform station-keeping*

- **Aid downlink**
  - *Data processing and compression to reduce downlink requirements*
  - *Enable direct downlink to users*

Onboard Processing – Technology

- **Hardware development**
  - *State of the art:*
    - *Onboard storage: ~10 Tb, ~9 Gbps flash memory (NISAR Solid State Recorder)*
    - *Onboard processors: e.g. 50 MHz 32-bit ARM*
    - *ADCs/Correlators: 3 GHz*
  - *Technology development needed:*
    - *Rad-hard-by-design tools and 3D IC technology to improve performance and SWAP*
    - *Fast ADCs, ASIC polyphase spectrometers*
  - *Desired state:*
    - *Increased capacity & speed; decreased SWAP-C for storage and microprocessors*
    - *ADC w/ BW > 20 GHz, ENOB > 4, power < 2 W*
    - *Spectrometers w/ BW > 20 GHz (10 GHz I/Q), 1 MHz res*
    - *Spectrometers w/ BW ~ 2-3 GHz, 128 channels, < 2 W for low-freq RFI mitigation*

- **Algorithm/software development**
  - *Compressive sensing (e.g., sparse multi-sat apertures)*
  - *RFI detection and mitigation*
  - *Data compression*
  - *Efficient data processing (may be instrument-specific)*

Spacecraft Control and Communication

- **Smallsat constellations/formations**
  - *Replace big and expensive with small and cheap*
  - *System design requires modeling and simulation*
  - *Precise (~cm level) formation control requires low-SWAP-C inter-spacecraft metrology, communication, and processing systems development*

- **Adaptive tasking**
  - *Develop capability for systems to detect terrestrial events (e.g., storms) and autonomously alter collection strategies in response*
  - *Rapid, automated self-tipping and vehicle-to-vehicle coordinated retasking*
  - *Low-latency (~minutes) space-to-ground-to-space retasking*
  - *Requires onboard processing, inter-s/c links, CONOPS development*

- **Downlink**
  - *System must accommodate ever-increasing data volumes*
    - *NISAR alone ~ 3-4 Gbps*
    - *Other high-rate systems (LIST, ICESat-2, etc) may also approach ~Gbps levels*
  - *May require new infrastructure*
    - *Additional relays/ground stations*
    - *Optical links*

Ground Processing

- **Develop next-generation architecture to manage large amounts of data**
  - *Storage (NISAR alone will produce ~petabytes per year)*
  - *Processing (NISAR ~TeraFLOPs)*
  - *Dissemination – user interfaces, infrastructure*

- **Develop CONOPS to enable quick-turnaround, event-driven tasking**
  - *Real-time processing, automatic feature recognition*
  - *Responsive (~minutes) spacecraft commanding (automatic or human-in-the-loop)*
  - *Coordination of multiple sensors*

- **Develop standards, interfaces, and infrastructure to allow big data fusion, code/library sharing**
  - *Systems/protocols to store and/or access data from multiple sources (e.g., space-based instrument data, airborne data, buoy data, etc.)*
  - *Real-time model predictions on same time and spatial scales as data*

- **Flexible dissemination of scientific data and products**
  - *User interfaces to facilitate data mining, fusion*

Algorithms/Models

- **Modeling, simulation, and algorithm development**
  - *‘Technology’ vs. ‘Engineering’*
  - *Instrument-specific, evolutionary retrieval algorithm development will be lower priority*
  - *Algorithms and models that are measurement-enabling or that transcend multiple measurement scenarios are more likely to merit investment*

- **Enabling or transcendent examples**
  - *RFI detection and mitigation techniques*
  - *Data compression algorithms*
  - *Software-defined/cognitive radiometry/radar*
  - *Compressive sensing (e.g. sparse cubesat apertures)*
  - *Formation modeling and simulation; onboard control algorithms*

Preliminary Conclusions and Recommendations

- **Emerging data-handling needs**
  - *Empirical, event-driven adaptive tasking and processing*
  - *Formation control*
  - *High data volumes/rates*

- **Investments required**
  - *Onboard processing hardware and algorithms, tasking CONOPS*
  - *Compressive sensing, formation modeling, inter-s/c metrology and communication*
  - *Data compression, down/crosslink infrastructure, ground data management*

- **Prioritize investments that enable measurements and/or transcend specific instruments**
  - *Onboard processing – RFI mitigation, data reduction and compression*
  - *Spacecraft control and communications – formation control, wideband downlinks*
  - *Ground – standards, interfaces, architectures, CONOPS, and infrastructure that enable big data storage and processing, sensor coordination, data fusion, sharing*
  - *Algorithms – modeling, simulation, and data processing*

Questions & Comments

NASA ESTO Microwave Technology Community Forum

March 17, 2016

EDT/PDT:	
11:00/08:00	Welcome/Overview of ESTO Investment Strategy Update (A. Valinia, NASA/ESTO)
11:20/08:20	State-of-the-Art and Future Requirements in Radar (F. Kantrowitz, Aerospace)
12:20/09:20	State-of-the-Art and Future Requirements in Microwave Radiometry (D. Kunkee, Aerospace)
13:20/10:20	*Break*
13:35/10:35	Data and Information Processing Future Requirements (A. Chandler, Aerospace)
14:15/11:15	Emerging Technologies and Trends (D. Kunkee, Aerospace)
15:00/12:00	Additional Input from Workshop Participants (All)
16:00/13:00	*Adjourn*

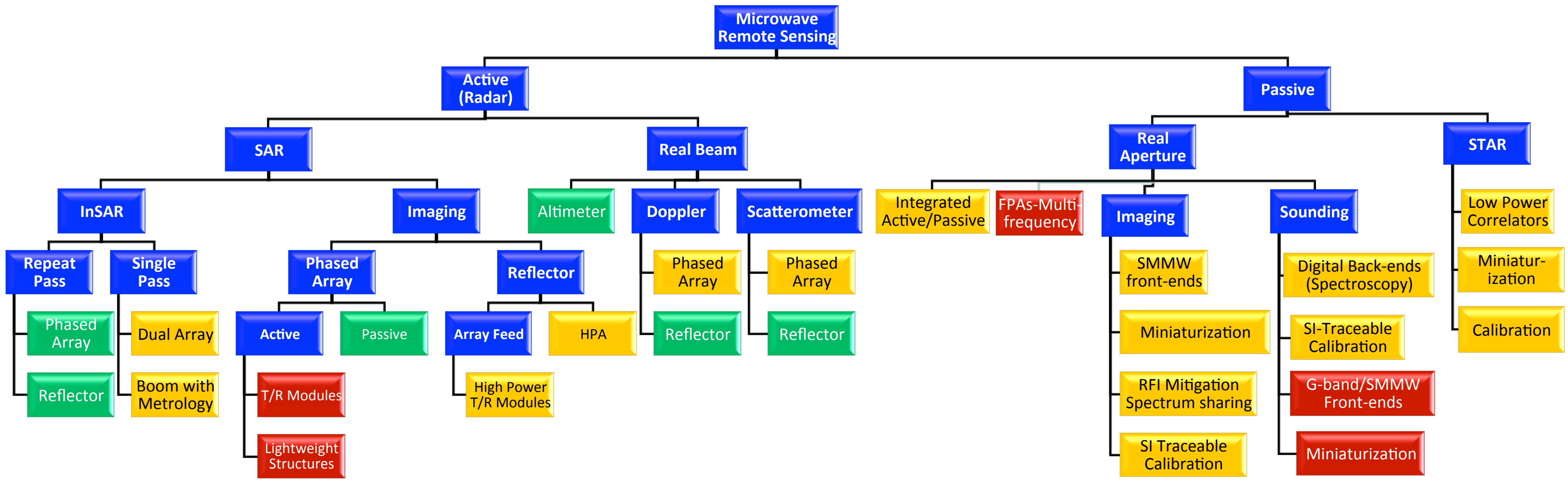
NASA ESTO Microwave Technology Status Evaluation:

Emerging Technologies Assessment

Contents

- **Microwave remote sensing taxonomy for Next Generation Measurements**
  - *Classification and categorization of technology development areas discussed in the previous sections*
  - *Space-based and Airborne versions to be developed*
- **Definition of emerging technologies**
- **Summary of emerging technology needs for new measurement concepts**
  - *Table showing Capability Gaps, Measurements, Current TRL assessment*
  - *General Observations (discussion slide)*
- **Presentation of combined emerging technology development needs**
  - *Detailed description by general technology areas (e.g. high frequency; miniaturization etc.)*
  - *Combined Radar, Radiometry, Information and Data Processing needs for each technology area*
- **Emerging technology roll up**
  - Separated into four general frequency groups spanning P-band to SMMW
- **Summary and Recommendations**
- **Q&A**

Microwave Remote Sensing Taxonomy for Next Generation Measurements (Space)

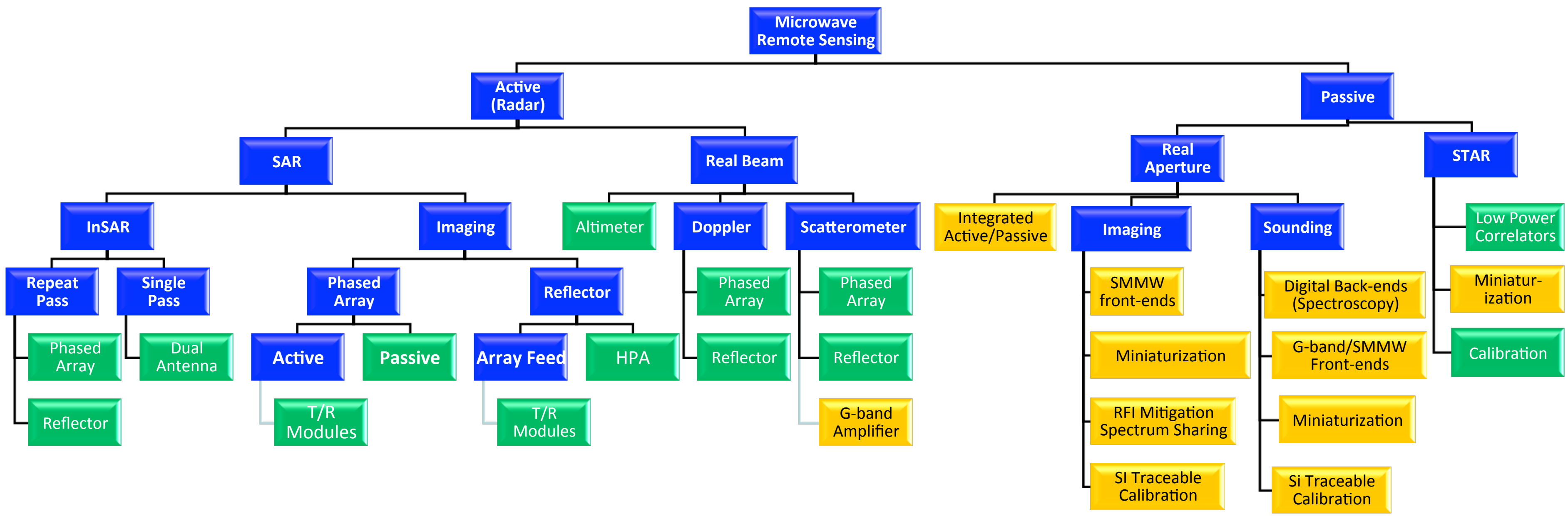


Key:

Space-Proven (TRL 7-9)
Developmental (TRL 4-6)
Experimental (TRL 1-3)

Each sensor/measurement has its own Command and Data Handling 'shadow', in addition to the cross-cutting IT challenges.

Microwave Remote Sensing Taxonomy for Next Generation Measurements (Airborne)



Key:

Flight-Proven (TRL 7-9)
Developmental (TRL 4-6)
Experimental (TRL 1-3)

Each sensor/measurement has its own Command and Data Handling ‘shadow’, in addition to the cross-cutting IT challenges.

Emerging Technology Definitions

- **Since the 2004 MWG report there has been a revolution in smallsat/hosted payload concepts, fueled in part by an increasingly (even aggressively) cost-constrained environment**
  - *In this paradigm miniaturization and low SWaP-C is key*
  - *Added low-cost launch opportunities create new measurement scenarios that were not envisioned in 2004*
  - *A new class/size range of deployable antennas is needed where overly restrictive stowed volume constraints are inconsistent with diffraction limited apertures of fixed size*
  - *May pursue ESPA-class launch volume sensors as a value added stowed volume constraint compared with cubesats*
- **The decision to actively address this emerging technologies in the 2016 report reflects a realization that new capabilities could greatly facilitate missions and measurement concepts**
  - *In this sense these new capabilities and the impact of increased access to space by universities and commercial interests cam impact approach to achieve new measurements*
- **For the current purpose we defined emerging technologies as being at a maturity level of <TRL3**
  - *TRL 2 is the entry point for ESTO's ACT and AIST programs*
- **System engineering as an emerging technology**
  - *Trades between aperture size, transmit power, altitude, integration of multiple sensor operating bands and/or active/ passive sensors sharing a single aperture can greatly influence 'best value' in achieving a measurement*
  - *Requires robust, high-fidelity modeling and simulation capabilities that accurately represent the critical elements in science and engineering, of trade. This can be horizontal and vertical spatial resolution; radiometric resolution or sensitivity, temporal resolution or revisit time as well as SWaP-C.*
  - *Closely couple technology needs to measurement needs and flow requirements using model-based engineering and system engineering principles*

Emerging Technology for New Measurements

Capability Gap	Measurements	Current TRL
G-band technology at ultra low SWaP and transmitter technology for Radar	Humidity profiles	2
SMMW technology at ultra-low SWaP	Cloud Ice and Atmospheric Processes	2
RFI Mitigation improvements	Wideband spectrometer/ algorithms	2-3
Integrated Radar/Radiometer or multi-frequency Front-ends	Root Zone/Sea Surface Salinity/ Air Sea Flux	2-3
Very large antennas	Weather radar, hazard warning surface deformation, volcanic activity, ice	2
Inter-spacecraft metrology for formation control (aperture synthesis in formation flying)	Root zone soil moisture	2
High-speed, high-res correlators /spectrometers	Atmospheric composition; RFI mitigation	2-5
Constellation management for small satellites: platform reliability, data routing and management, system engineering tools	Root Zone Soil Moisture, Precipitation, Atmospheric Humidity	2

General Observations

- **TRL assessments depend on specific measurement attributes that did not appear to currently be firm**
  - Performance targets will dictate maturity and TRL
  - Some requirements were asserted for measurements (SWaP targets; correlator performance)

- **Multiple approaches to achieve new measurements in some cases**
  - High temporal revisits from LEO or GEO scanning approach
  - Integrated sensors with aperture sharing vs. separate sensor platforms
  - Adaptive tasking and coordination of multiple s/c vs. autonomous systems with continuous coverage

- **Multiple directions for some technology improvements**
  - *Direct detection vs. low power heterodyne configurations for G-band*
  - *Deployable 2-m class apertures from CubeSat or ESPA-class stowed volumes*
  - *Synthetic thinned aperture (correlators) vs real aperture (passive); Phased array vs. reflector apertures (Radar)*

- **Cross-cutting needs that would benefit multiple measurements**
  - High frequency (G-band and higher) improvements to SWaP-C and performance
  - Multi-frequency feed technologies to enable cost-effective multi-frequency/sensor measurements scenarios
  - Wide-band digital backend processing for RFI, spectrometry and polarimetry (passive), array feeds for reflectors

High Frequency RF Components and Systems

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Front-end LNAs	Cloud Ice Atmospheric Composition Humidity	T_{sys}~350 K at 183-GHz; T_{sys}>800 K at 500 – 600 GHz	T_{sys}~300 K @ 500-GHz and 20 K ambient Power < 0.1W; Mass < 200g
Low Power Consumption LOs;	Cloud Ice Atmospheric Composition Humidity	GDOs or DROs + Multipliers >100mW DC power for ~10dBm RF output	MMIC-based superheterodyne integrated receivers: 300K at room temp @183 GHz Power <0.05W;mass<100g <1W; high level of integration; 5-10mW output up to 900 GHz
Ultra low power mmW front-ends	Water vapor and aerosol/cloud profiles	Combination of MMIC followed by CMOS receiver chipset has been demonstrated but only to 94 GHz; 300K at room temp @94 GHz Power <0.2W;mass<100g	300K noise temperature at room temp @183 GHz; Power <0.05W; mass<100g
G-band MMICs T/R modules; HPAs	Humidity; Cloud Ice	*Under review*	1-10W W-band T/R modules with integrated PA, LNA, phase shifter (4-bit), low loss T/R switches;. 1W PA and CW source; GaN

Multiple Frequency Integrated Elements (e.g. FPAs)

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Broadband integration of radiometer and radar transmitter and receiver modules	Root Zone Soil Moisture Sea Surface Salinity Air-Sea Flux Sea Ice	Separate instruments or narrow band diplexer	Frequency range P/ L/ S-bands (400 MHz through 2-GHz) Low impact to the operation and performance of either sensor while reducing SWaP-C for multiple band measurements
Integration of Radar transmitter and receivers with radiometry	Precipitation	Frequency multiplexors and separate receiver chains	Instrument front-end with small SWaP; allows use of many units with fleet of cubesats
Integration of radar transmitter and receiver/ polarimeter	Ocean Altimetry Ocean Winds	Separate instruments	Single radar/ radiometer/ polarimeter to perform Ocean altimetry and/or scatterometry combined with polarimetry (passive)

Miniaturization of Sensors (SWaP; Deployables)

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
2-m class deployable antenna	Improved HSR for traditional measurements from small satellites; Precipitation Ocean Surface Winds Sea Ice Cloud liquid	6-m+ class deployable from larger rocket fairings; 0.7m deployable (TRL 6) from 1.5U; up to ~40 GHz for communication applications	Performance to ~600 GHz; stowed volume ~ 2.5U
MMIC-based radiometers and focal plane arrays covering multiple bands	Precipitation; Sea Ice; Cloud Liquid; Land Surface Characteristics	Discrete components and large feedhorn arrays driving SWaP for multi-band radiometer systems	Compact radiometer and reflector feed systems with deployable antennas reducing SWaP-C of traditional radiometer systems

Large Reflectors and Lightweight Materials

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Very Large Antennas	Weather Radar, Surface Deformation, Volcanic Ash, Ice	10-m class reflector antennas (Communications pedigree)	Larger deployable antennas
Lightweight antenna structures	Weather Radar (persistent cloud /storm observation), Seismology, Hazard monitoring	Ground based, L-band, Doppler Weather radar	Space-based persistent observation

Sensor Calibration (Radiometers)

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Direct SI-Traceable Calibration	In order of priority: Atmospheric Temperature Profile, Precipitation (multiple radiometers); water vapor, ocean surface and clouds	Individual radiometer cal/val and Cross calibration analysis with other radiometers	Uniform calibration between fleet sensors all traced to SI-standard
Improved Calibration of UAV-based Radiometers	Tasked observations of Precipitation/ Hurricanes or atmospheric temperature	Internal calibration targets and thermal sensors	Combine information about ambient environment to improve unattended airborne (vs. space-based) instrument calibration and achieve uniform calibration among several sensors and platforms
Distributed calibration for Synthetic Thinned Aperture Radiometers	Atmospheric Temperature, Water Vapor and Precipitation	*Under review*	*Under review*

Digital Processing Performance Improvements

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
High Speed Digital Backends	Atmospheric Composition; Polarimetry (OSWV; EPBR)	20-GHz Digital back-end	50-GHz
Broadband Radiometers	Imaging radiometry in areas of significant RF contamination	RFI detection and mitigation in BWs up to ~500 MHz	Spectrometer to support measurements anywhere from 1 – 50 GHz
Distributed Correlators	Root Zone Soil Moisture	Correlation of several small antennas within fixed frame	< 100 MHz BW with limited baselines in constellation

Next Generation Data Processing and Management

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Ground data management	Weather prediction; L3 / L4 products from L2 products; Atmospheric boundary layer dynamics; global circulation	Mission centric data processing to L2 data and distribution to a few centers	Evolving data assimilation and fusion of L1/2 data to larger systems (e.g. NWP); 'global' distribution of vetted higher level products
Inter-spacecraft metrology for formation control	Root Zone Soil Moisture; Precipitation	Independent platform attitude control; limited dual satellite control (GRACE)	Inter-spacecraft metrology for formation control; control/ knowledge adequate to synthesize larger apertures using formation flying of small satellites
Fast external data links	Weather imagery; precipitation events	Data downlinks and ground based data exchange	Fast external data links; data sharing in formation to facilitate data processing/ attitude control; autonomous tasking

Emerging Technology Roll-up

	P- /S-band 400-MHz to 2-GHz	C- /W-band 6- to 90-GHz	W- /G-band 100- to 200-GHz	SMMW 300-GHz to 1-THz
Measurement	Root Zone SM; SSS;	OSWV; SST; Imagery Ocean Altimetry; IWV Atmospheric Sounding; Cloud Amount; SWE	Atmospheric Temperature and water vapor profiles	Cloud characterization; cloud Ice
Antenna/ Aperture	Up to 10m aperture vs. distributed correlation systems; Larger antennas for radar	Up to 7m aperture(s); multi-band FPA; cylindrical / offset parabola; STAR at GEO	Deployable 2m dia from 2.5U stowed volume – various altitudes	Deployable up to 1m – various altitudes
Radiometer	RFI mitigation – tunable notches, broadband radiometers; frequency agile	Low SWaP-C radiometers integrate-able with Radar systems	Low SWaP-C radiometers; Low power LOs; Direct detection; filter technology	Low SWaP-C radiometers; low power LOs; direct detection; LNA performance
Radar	T/R modules – extend down to P-band	C-/X-band Mature; W-band GaN T/R Modules	GaN T/R modules for higher efficiency; HPAs, very small SSPAs	N/A
Platform	3-D ranging; formation flying; UAV	Reliable 5yr cube-sat bus; UAV; imaging on demand (hurricanes/storms);	Reliable 5yr cube-sat bus; higher power;	Reliable 5yr cube-sat bus; higher power;
IT/ Data processing	Multi-sensor processor: Passive/Active/SoOp	Small sat data transmission;	Small sat data transmission;	Small sat data transmission;

Preliminary Conclusions and Recommendations

- **Multi-band integrated active/passive front-ends**
- **Multi-band phased array feeds for array–fed reflector based radars**
  - *High power, efficient GaN T/R modules*
- **Digital radar electronics**
  - *Waveform generators, beamforming, receivers*
  - *Apply cubesat technology to larger sats*
- **High frequency RF components and systems**
  - *Each constitutes a waypoint on the small-sat/U-class constellation roadmap*
- **Miniaturization of sensors to leverage low-cost and hosted launch opportunities**
  - *Cubesats – some measurements concepts drive very low TRL assessments*
  - *ESPA-class – may provide better value technology development targets depending on measurement parameters*
- **Higher digitization rates and data processing**
  - *Enables a wide range of capabilities RFI mitigation, spectrum sharing, spectrometers, polarimeters*
- **Radiometer Calibration**
  - *Different configurations of radiometers (shared aperture, STAR, UAV, formation flying, SI traceability)*
- **Next generation data management and communication**
  - *Microwave sensors require data handling from distributed systems without data volume constraints*

Questions & Comments

NASA ESTO Microwave Technology Community Forum

March 17, 2016

EDT/PDT:	
11:00/08:00	Welcome/Overview of ESTO Investment Strategy Update (A. Valinia, NASA/ESTO)
11:20/08:20	State-of-the-Art and Future Requirements in Radar (F. Kantrowitz, Aerospace)
12:20/09:20	State-of-the-Art and Future Requirements in Microwave Radiometry (D. Kunkee, Aerospace)
13:20/10:20	*Break*
13:35/10:35	Data and Information Processing Future Requirements (A. Chandler, Aerospace)
14:15/11:15	Emerging Technologies and Trends (D. Kunkee, Aerospace)
15:00/12:00	Additional Input from Workshop Participants (All)
16:00/13:00	*Adjourn*

Community Input

NASA ESTO Microwave Technology Community Forum

March 17, 2016

EDT/PDT:	
11:00/08:00	Welcome/Overview of ESTO Investment Strategy Update (A. Valinia, NASA/ESTO)
11:20/08:20	State-of-the-Art and Future Requirements in Radar (F. Kantrowitz, Aerospace)
12:20/09:20	State-of-the-Art and Future Requirements in Microwave Radiometry (D. Kunkee, Aerospace)
13:20/10:20	*Break*
13:35/10:35	Data and Information Processing Future Requirements (A. Chandler, Aerospace)
14:15/11:15	Emerging Technologies and Trends (D. Kunkee, Aerospace)
15:00/12:00	Additional Input from Workshop Participants (All)
16:00/13:00	*Adjourn*

Backup

TRL Definitions

TRL	Definition	Hardware Description	Software Description	Exit Criteria
1	Basic principles observed and reported	Scientific knowledge generated underpinning hardware technology concepts/applications.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated	Invention begins, practical applications is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Practical application is identified but is speculative; no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations, and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental critical function and/or characteristic proof-of- concept	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experimental results validating predictions of key parameters.

TRL Definitions (cont.)

TRL	Definition	Hardware Description	Software Description	Exit Criteria
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to final operating environment.	Key, functionality critical software components are integrated and functionally validated to establish interoperability and begin architecture development. Relevant environments defined and performance in the environment predicted.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Component and/or breadboard validation in relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrate overall performance in critical areas. Performance predictions are made for subsequent development phases.	End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.

TRL Definitions (cont.)

TRL	Definition	Hardware Description	Software Description	Exit Criteria
6	System/sub-system model or prototype demonstration in a relevant environment.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Prototype implementations of the software demonstrated on full-scale, realistic problems. Partially integrated with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.