NASA TROPICS Pathfinder Low Latency Data Demonstration Results

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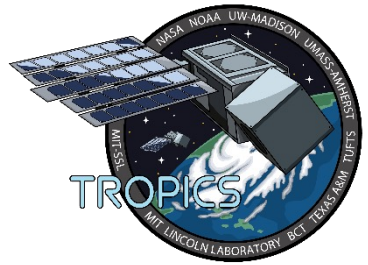
23 June 2022



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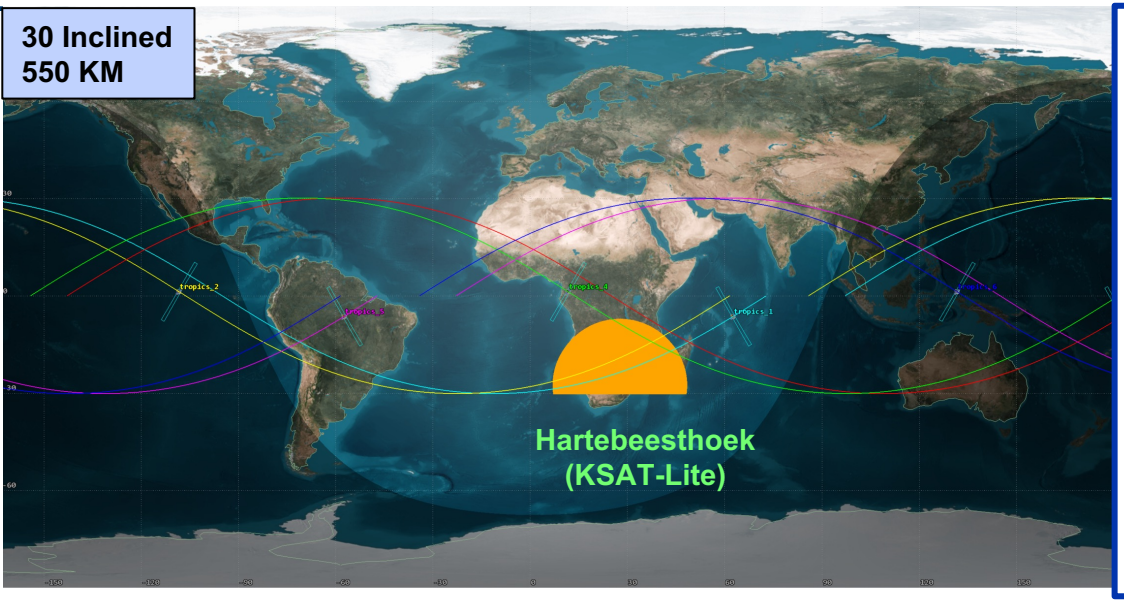
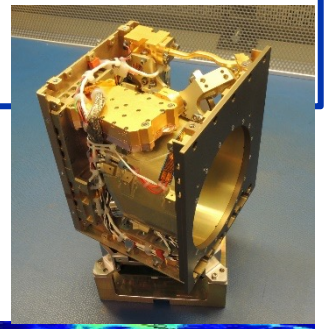
- **TROPICS and Pathfinder**

- **NOAA Pathfinder Low Latency Demo**
  - **TROPICS Constellation NRT**

TROPICS: Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats



- NASA Earth Venture Instrument Program
  - Principal Investigator: Dr. Bill Blackwell
- Innovative solution to provide data for severe storm intensity forecasts
  - Temperature, water vapor, precipitation, and cloud properties
- Six satellite constellation of 3U cubesats
  - 2U spacecraft from Blue Canyon Technologies (BCT)
  - 1U MIT LL Instrument: multi-channel passive compact microwave radiometer
  - Better than 60 minute median revisit time



KSAT

Ground Station Network

BCT

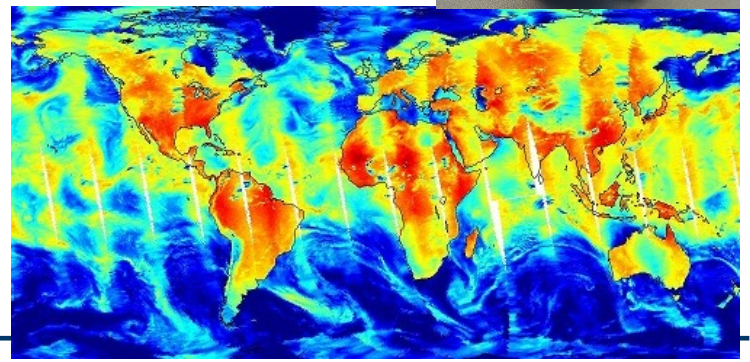
Mission Operations Center

MIT LL

Science and Payload Operations Center

UW-SSEC

Data Processing Center



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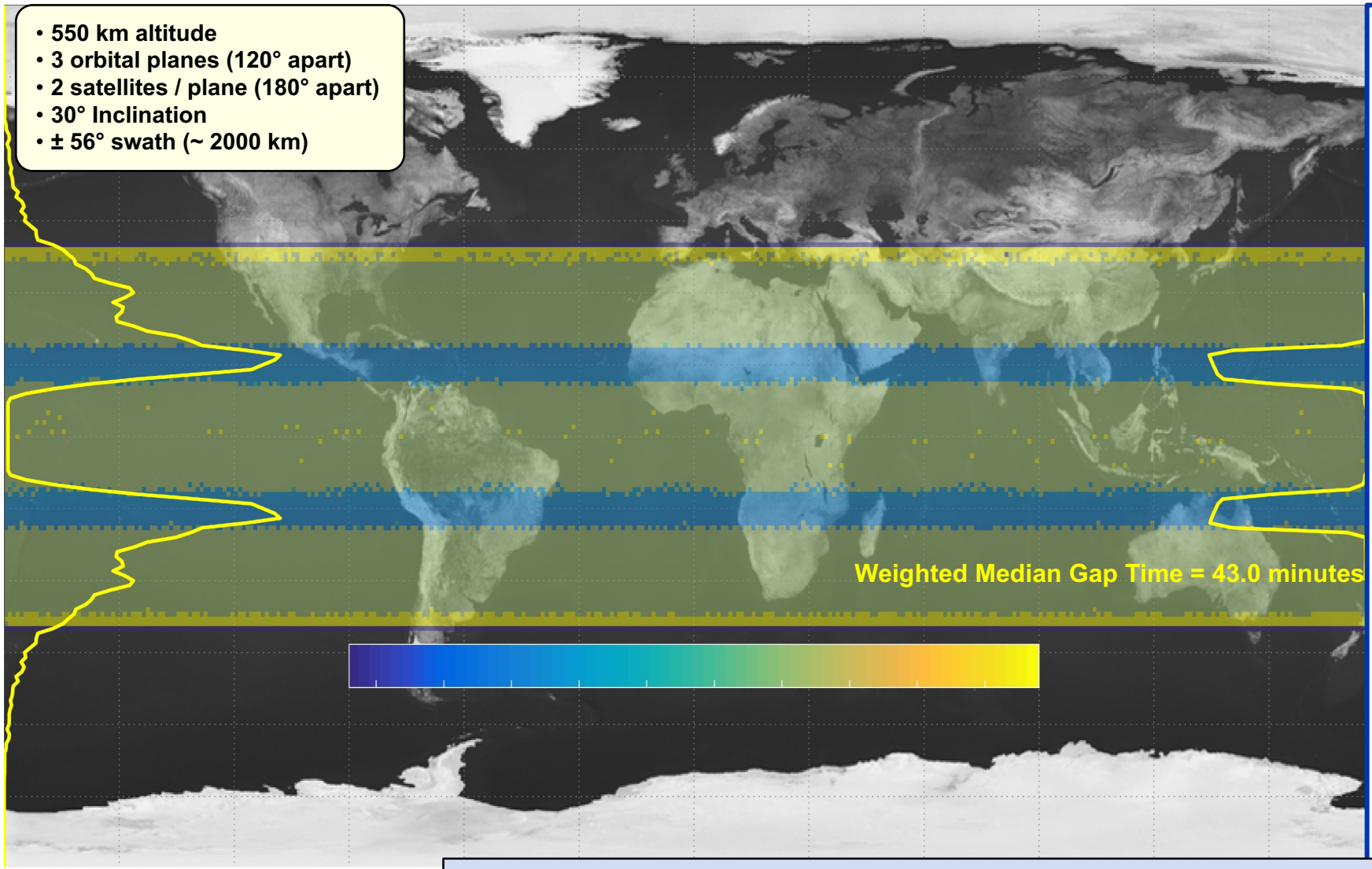
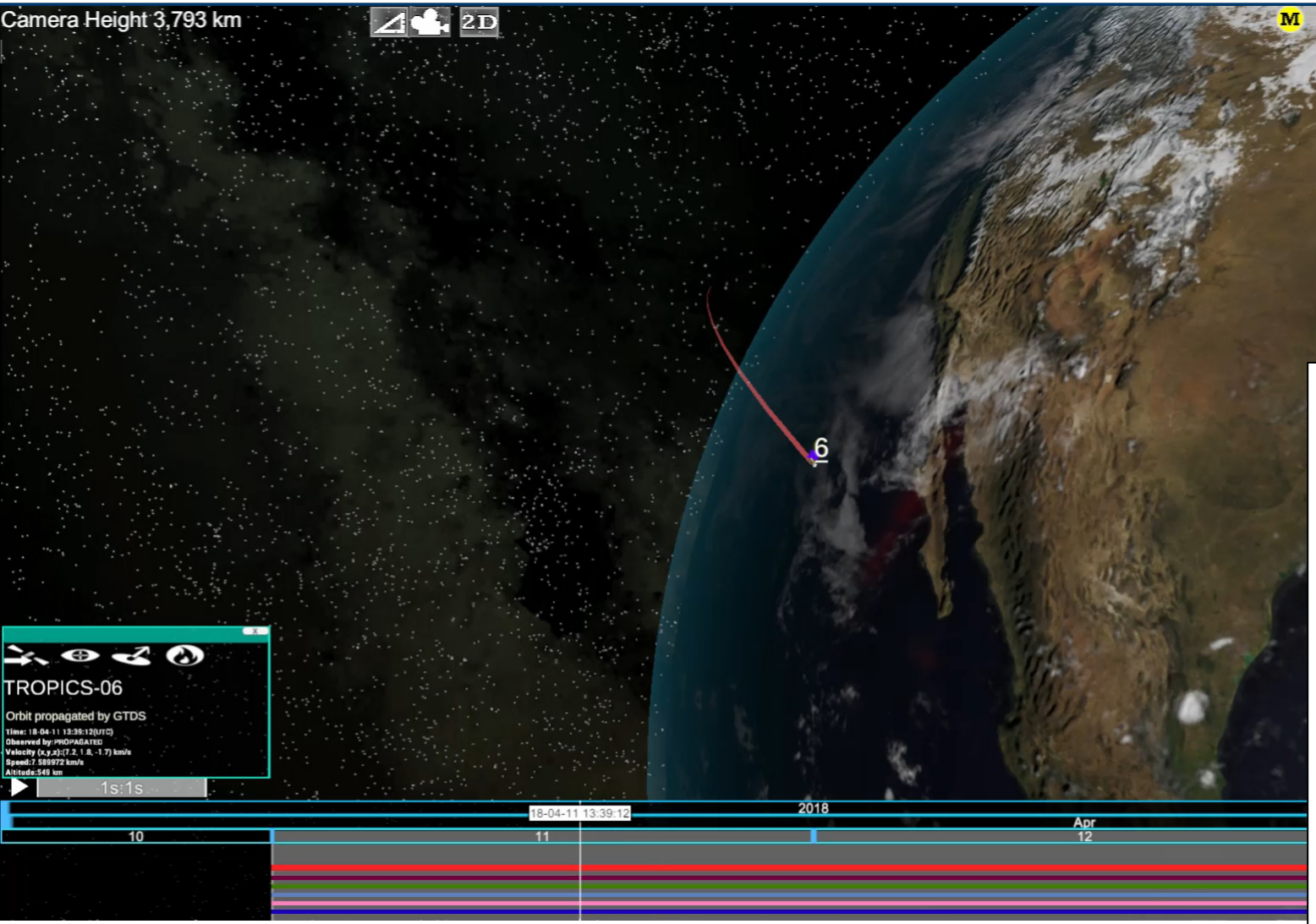
TROPICS Operational CONOPS



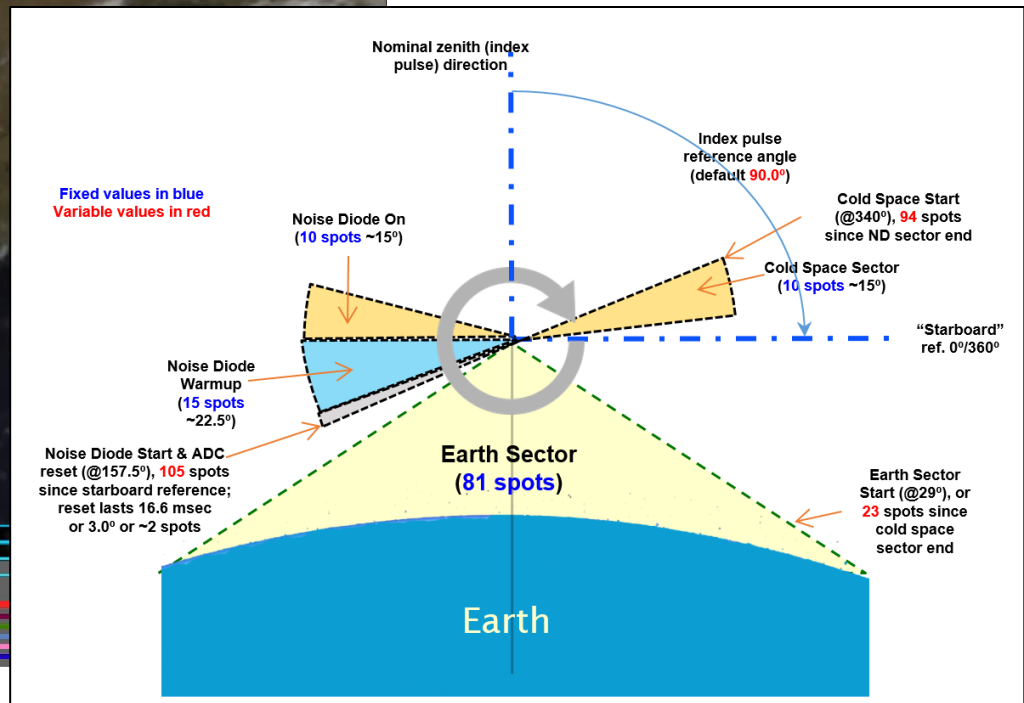
- < 60 minute median revisit rate
  - Payload nominally operates on a 24/7 duty cycle
- TROPICS CONOP is to downlink all data collected from the space vehicle
  - Science data cannot be recorded during ground contact
- Currently there is no latency downlink requirement from the space vehicle
  - TROPICS requires an average of 3 downlinks per space vehicle per day to meet data downlink requirements
- TROPICS currently uses one KSAT-Lite ground station in Hartebeesthoek
  - More ground stations are being added…

Nominal Downlink Latency is ~4 hours

TROPICS Payload



- **1U multi-channel passive compact microwave radiometer**
  - **12 Channels (G, W and F Band)**
  - **30 RPM spinning payload**
  - **Integrated noise diode for on orbit calibration**



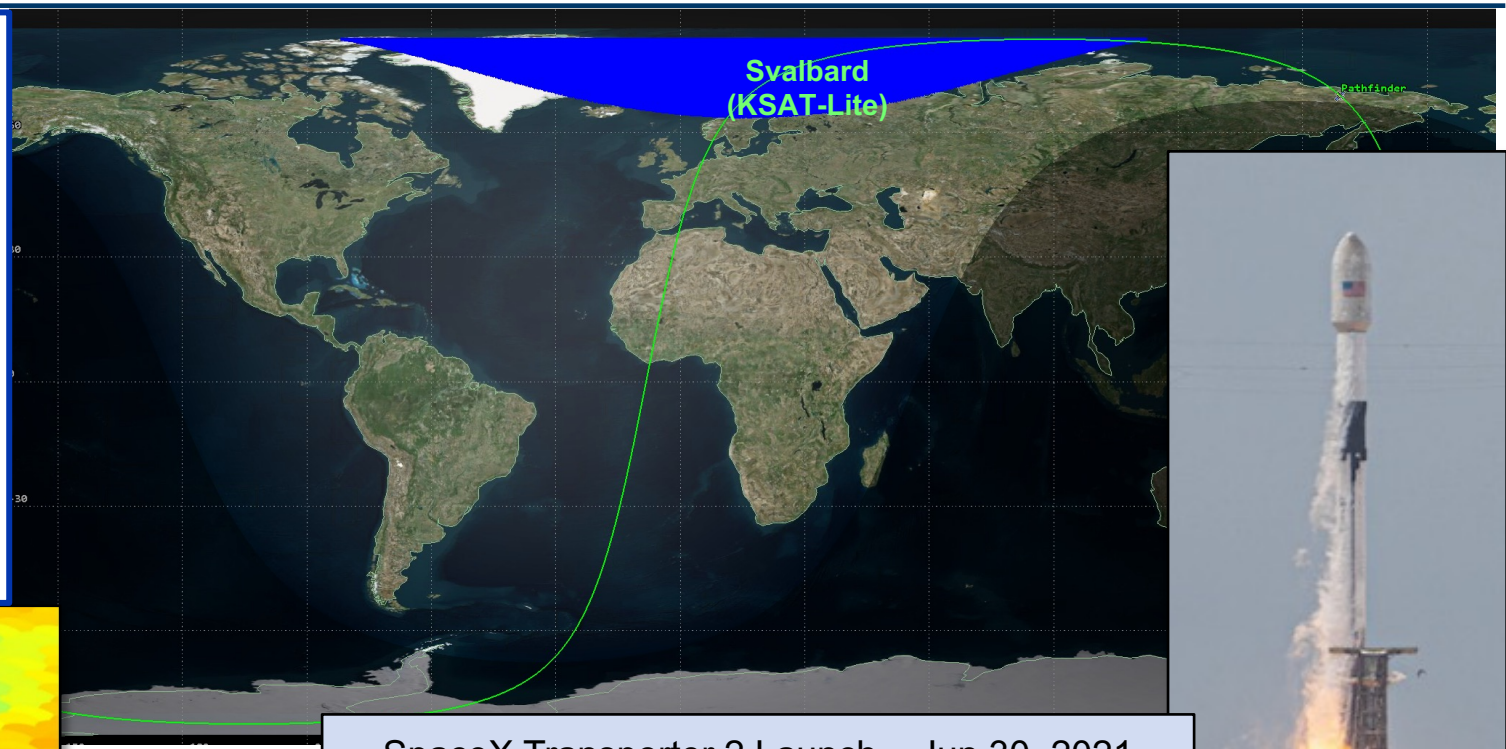
Notes:
Space vehicle velocity vector is INTO the page; LVLH attitude shown
1 spot ≈ 0.008331 seconds (≈ 1.5° at 30.0 RPM)
Angle swept per spot is a function of scanner rate

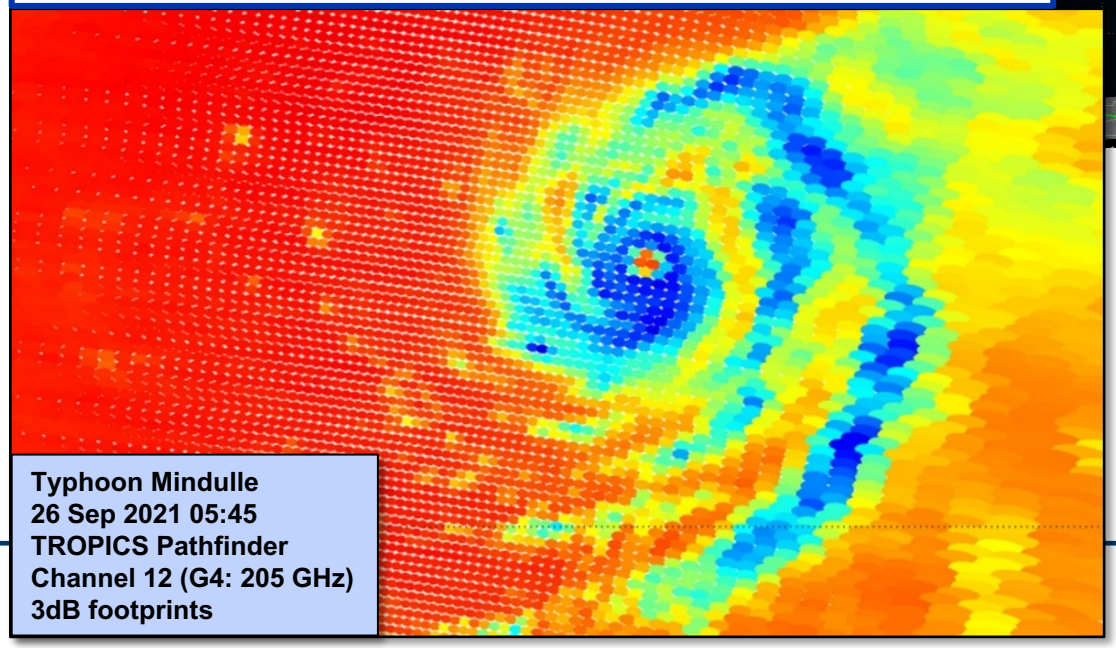
TROPICS/Pathfinder

- Since 2016, Lincoln Laboratory has been executing the TROPICS program for NASA to build and launch a constellation of six 3U CubeSats
  - The constellation was completed in June 2020 and were put in storage while NASA selected a dedicated launch provider to insert them into their unique, 30-degree inclined orbit
  - Current launch schedule is TBD
- In the meantime, Lincoln Laboratory and NASA upgraded the program's engineering design unit satellite to a flight unit and launched it aboard a SpaceX rideshare mission in June 2021.
  - This "Pathfinder" enabled the Laboratory to exercise all mission elements and to reduce risk for the constellation
  - TROPICS Pathfinder continues operate to this day

TROPICS Pathfinder

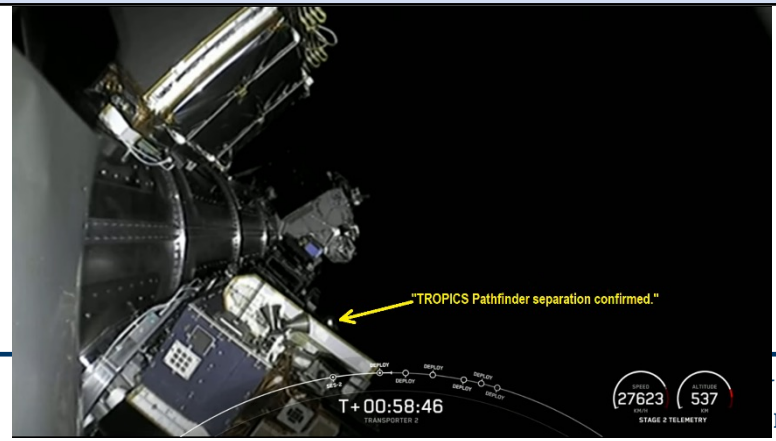
- MIT LL / NASA Funded mission
- TROPICS "Qualification" satellite launched into
  - Sun-Synchronous Orbit @ 97.5°
  - 525 km altitude, circular
- Launched prior to the constellation to verify software/hardware on orbit
  - Many lessons learned that were applied to the constellation
- June 30 2021 launch and still operating





Typhoon Mindulle
26 Sep 2021 05:45
TROPICS Pathfinder
Channel 12 (G4: 205 GHz)
3dB footprints

SpaceX Transporter 2 Launch – Jun 30, 2021



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- **TROPICS and Pathfinder**

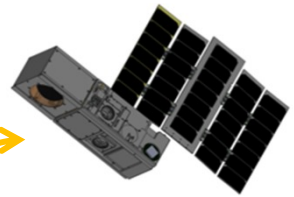
- **NOAA Pathfinder Low Latency Demo**
  - **TROPICS Constellation NRT**

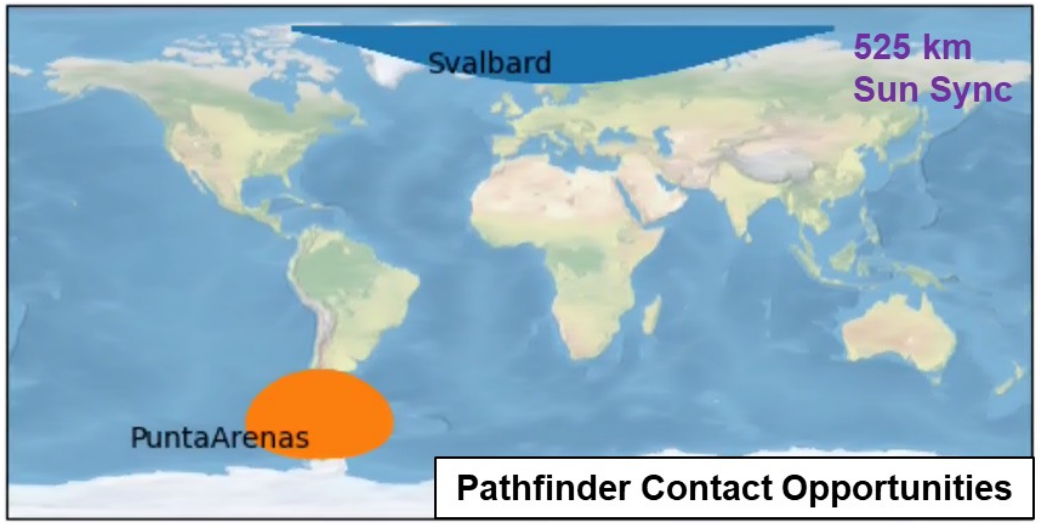
Pathfinder Low Latency Demo Overview

- This Low Latency demonstration was funded by NOAA to explore data latency reduction for weather forecasting using the Pathfinder satellite
  - TROPICS is a NASA ESSP science mission and does not have downlink latency requirements
  - Nominal Pathfinder latency is ~ 4 hours
- Objectives for the Low Latency Demo:
  - Reduce time between satellite measurements of weather phenomena to generation of associated L1 data products.
    - The demo scheduled ~17 contacts a day, compared to 3 required
  - Establish methods and software tools which will also enable the TROPICS constellation
    - All tools were developed with forward compatibility in mind

Pathfinder NRT Data Flow

RF
TCP/IP





Ground Station Network

KSAT-Lite

- Antenna commanding
- Data demodulation

Schedule TT&C

SV Data

Mission Operations Center

BCT

BLUE CANYON TECHNOLOGIES

- Contact scheduling
- Level 0 data packaging

CMDs

SV data Lvl0 Data

Science and Payload Operations Center

MIT LL

- Algorithm dev.
- Payload Monitoring
- Science trending

Algos

Lvl1

Lvl0 Data

Data Processing Center

UW-SSEC

- Data Processing (Lvl-0 to Lvl-1b)
- Data formatting & archiving (NetCDF and BUFR)

Lvl1

NOAA

NOAA

- BUFR data
- L1a and L1b processing

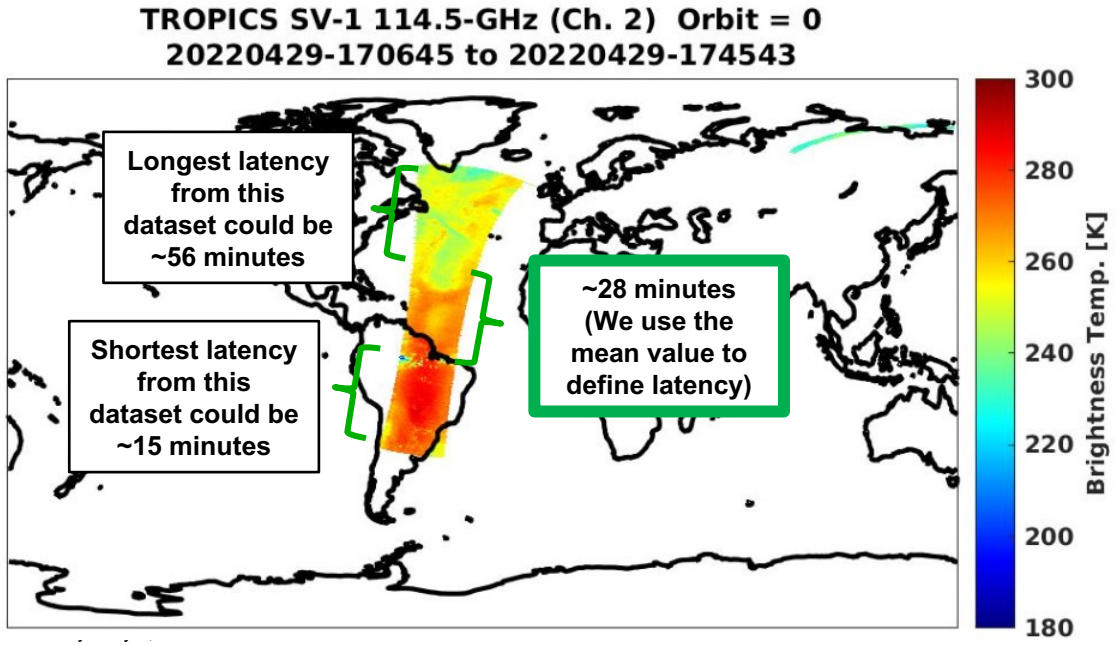
Latency Definition

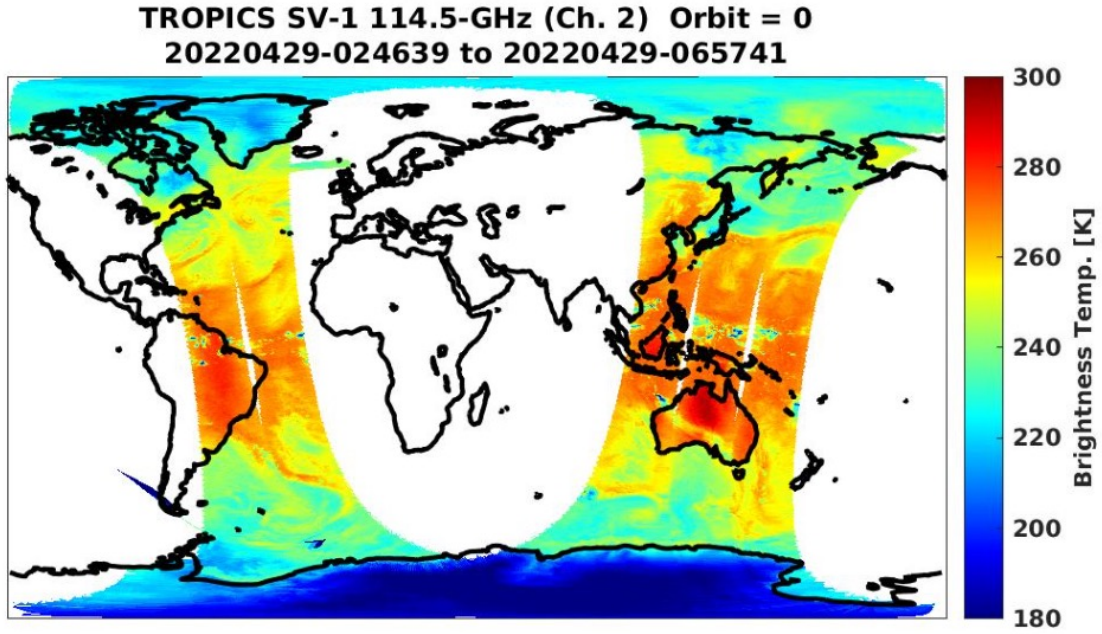
- **Latency: The average age of science data after processing has been completed**
  - **The average time from acquisition by the payload to processed Level 1 data product at the DPC (UWisc)**
- **Data files will include data acquired from the prior contact completion**
  - **Science data collected *during* a contact is not usable**
    - **Satellite body points, resulting in unusable data**
- **For simplicity, we do not factor in a target location, we consider all data equal!**
- **Latency definition:**
  - **Current contact loss of signal: T_n**
  - **Previous contact loss of signal: T_{n-1}**
  - **Processing time: P**
  - **Average latency: $(T_{n-1} - T_n)/2 + P$**

Demo Latency Examples

- **Lowest latency case: ~28 minutes**
  - **Previous contact in Svalbard: 16:19:20**
  - **Current contact in Punta Arenas: 17:07:31**
- **Orbit geometry permitted two contacts within a short timeline**

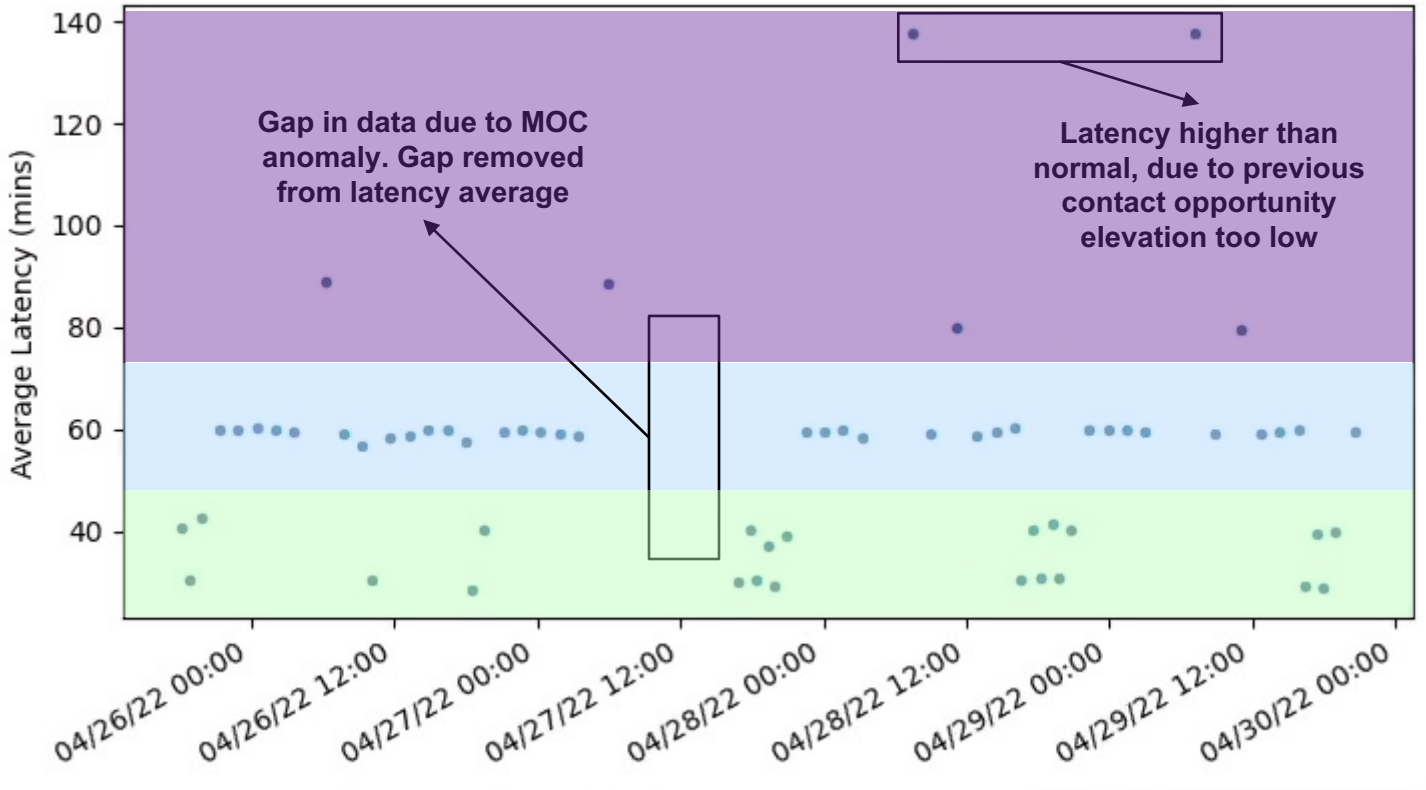
- **Longest latency case: ~140 minutes**
  - **Previous contact in Svalbard: 02:56:13**
  - **Current contact in Punta Arenas: 06:57:31**
- **Orbit geometry resulted in low elevation contacts, preventing Svalbard contacts**





Data Latency Results

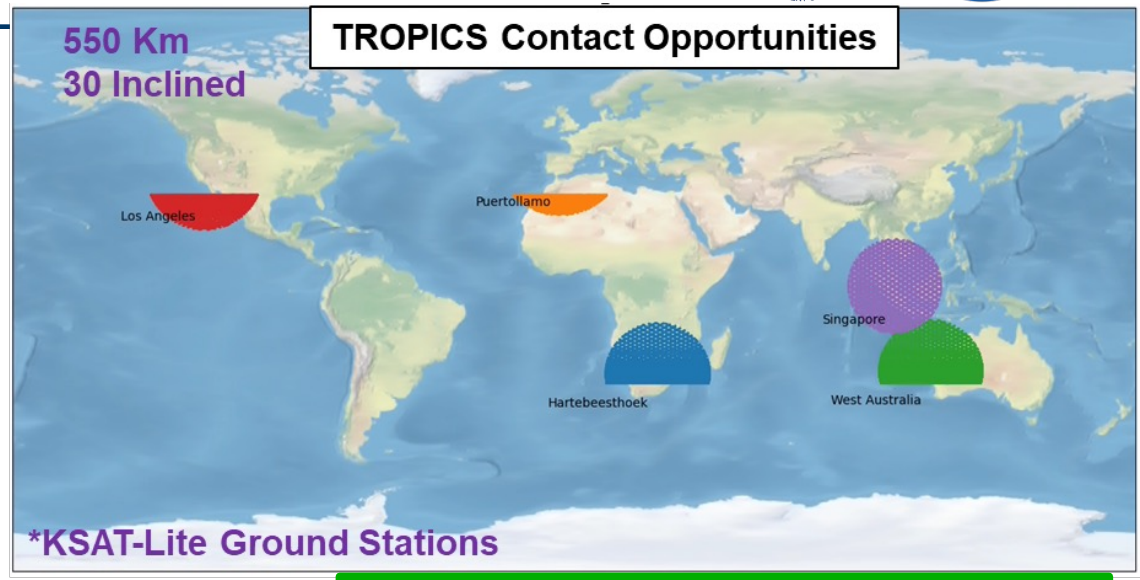
- 5 Day demo
- Demo start time: 4/25 13:27Z
- Latency numbers include processing time at the DPC
- Latency
  - Average latency: 55 mins
    - Removed MOC anomaly resulting in 4 missed contacts
  - Min latency: 28 mins
    - Low latency numbers, result of orbit geometry allowing contacts at both Svalbard *and* Punta Arenas
  - Max latency: 138 mins
    - Max due to an orbit without a schedule contact in Svalbard

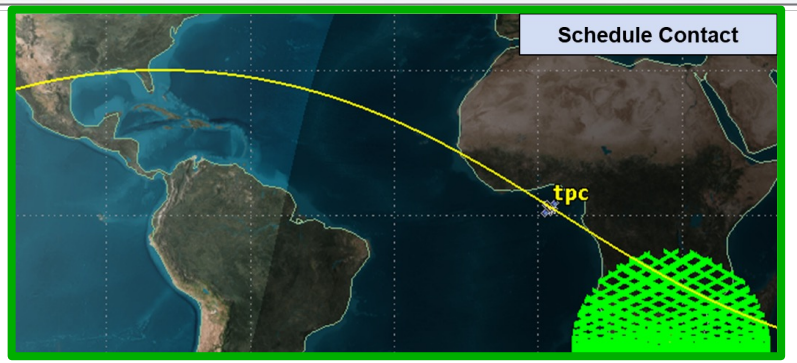


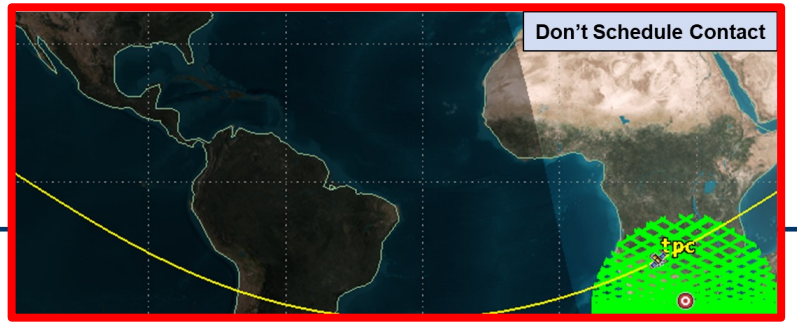
Latency improved from 240 minutes → 55 minutes

TROPICS Low Latency

- **Due to the TROPICS orbit and location of the KSAT-Lite ground stations the Atlantic and Indian Basin are optimal targets for low latency data**
- **Latency is average time from acquisition by the payload to processed Level 1 data product at the DPC**
  - **Level 2 products are in the process of being optimized for NRT**
- **Ground station availability is the enabler**
  - **ITU licensing for LA, Punta Arenas and West Australia (October → December of 2022)**
  - **Singapore completion ~Spring 2023**







Estimate Latency is ~45 minutes from Atlantic Basin

Summary

- This NOAA exercise demonstrated that the Pathfinder ground system can deliver Level 1 data products in <60 minute average latency
- Analysis shows that the TROPICS constellation should achieve <45 minute average latency to deliver Level 1 data products
  - Level 2 data processing efficiencies are being worked
- The TROPICS constellation median revisit of <60 minutes rate combined with <45 minute latency will be able to support applications such as
  - numerical weather forecasting
  - monitoring natural hazards (i.e., TCs, floods, and fires),
  - agriculture (i.e., harvesting times, drought conditions, and freeze protection), and
  - air quality (i.e., pollution and ultraviolet radiation exposure alerts).

Questions?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Backup

TROPICS Channel Set

TROPICS Ch.	W-band Ch.	Center Freq. (GHz)	Bandwidth (GHz)	RF Span (GHz)
1	W1	91.655 ± 2	1.000	89.155-90.155, 93.155-94.155

TROPICS Ch.	F-band Ch.	Center Freq. (GHz)	Bandwidth (GHz)	RF Span (GHz)
2	F1	114.50	1.000	114.00-115.00
3	F2	115.95	0.800	115.55-116.35
4	F3	116.65	0.600	116.35-116.95
5	F4	117.25	0.600	116.95-117.55
6	F5	117.80	0.500	117.55-118.05
7	F6	118.24	0.380	118.05-118.43
8	F7	118.58	0.300	118.43-118.73

TROPICS Ch.	G-band Ch.	Center Freq. (GHz)	Bandwidth (GHz)	RF Span (GHz)
9	G1	183.31 ± 1.0	0.500	182.06-182.56, 184.06-184.56
10	G2	183.31 ± 3.0	1.000	179.81-180.81, 185.81-186.81
11	G3	183.31 ± 7.0	2.000	175.31-177.31,189.31-191.31
12	G4	204.3	3.000	202.8-205.8

Ground Station Contacts

- **Ground station contacts scheduled by the MOC 3 days ahead of the contact**
  - **CONOP was to schedule as many contacts as possible**
    - **No requested contacts were denied due to KSAT-Lite conflicts**
    - **One anomaly where KSAT-Lite antennae couldn't track**
  - **Contacts scheduled via KSAT-Lite scheduling API, without any KSAT personal in the loop**

	Contacts	Notes
Monday	7	Started at MOC business hours (MTN)
Tuesday	17	
Wednesday	17	
Thursday	16	Skipped a low elevation contact
Friday	16	Skipped a low elevation contact

Overall Time Budget

Step	Estimate (avg mins)	Actuals (avg mins)	Notes
Downlink	38	43 (+5)	Estimates did not account for excluding low elevation contacts
MOC Processing	3	1 (-2)	MOC database improvements
DPC Processing	13	5 (-8)	L1B processing efficiency improvements
Total	54	49 (-5)	5 minutes faster than estimated prior to the demo!

- **Latency clock stopped after DPC processed L1B data product**
- **NOAA is going to pull/process on orbit data post demo for evaluation**
- **Level 2 data products were NOT exercised during Low Latency Demo**
  - **Level 2 products can take up to 3 → 47 minutes to process**

Lessons Learned

- Latency is primarily driven by ground station location and availability
- Multiple data requests in pass worked well, but 5 contacts still had data loss
  - Updated procedures could more efficiently manage data loss
  - Below ~12 degrees elevation data loss became more prevalent
- For the constellation we should intelligently schedule contacts based on desired target location
  - TROPICS pays per pass
  - If we target contacts with only new data from the Atlantic basin, we can reduce contact scheduling by ~50% and still achieve desired latency
  - Autonomous scheduling based on target location needs to be developed
- Level 2 data products require efficiency improvements to be used in a Low Latency mode of operation

Constellation Needs

Mission Operations

- **Constellation only has one operational ground station in Hartebeesthoek**
  - **Frequency licenses required to reduce latency:**
    - **Puertollano, West Australia, Los Angeles and Mauritius**
  - **TROPICS has a frequency license in Singapore**
    - **KSAT estimates the Singapore will be completed in ~May 2023**

      Current bottleneck is COVID construction delays (digging/pouring pad)
- **NRE funding to the MOC**
  - **Improve packet loss during low latency operations**
    - **Constellation vehicles implemented CFDP (CCSDS file transfer protocol), which provides a capability to re-transmit dropped packets on demand. MOC would need to implement retransmit logic to utilize CFDP functionality.**
  - **Improve efficiency of NRT scheduling (*if NRT is targeting a storm or basin*)**
    - **If NRT focuses in on the Atlantic basin, location based scheduling prioritization could reduce contact cost by ~$100K per month.**

      Location based scheduling would target downlinks only after the Atlantic basin crossing

Constellation Needs

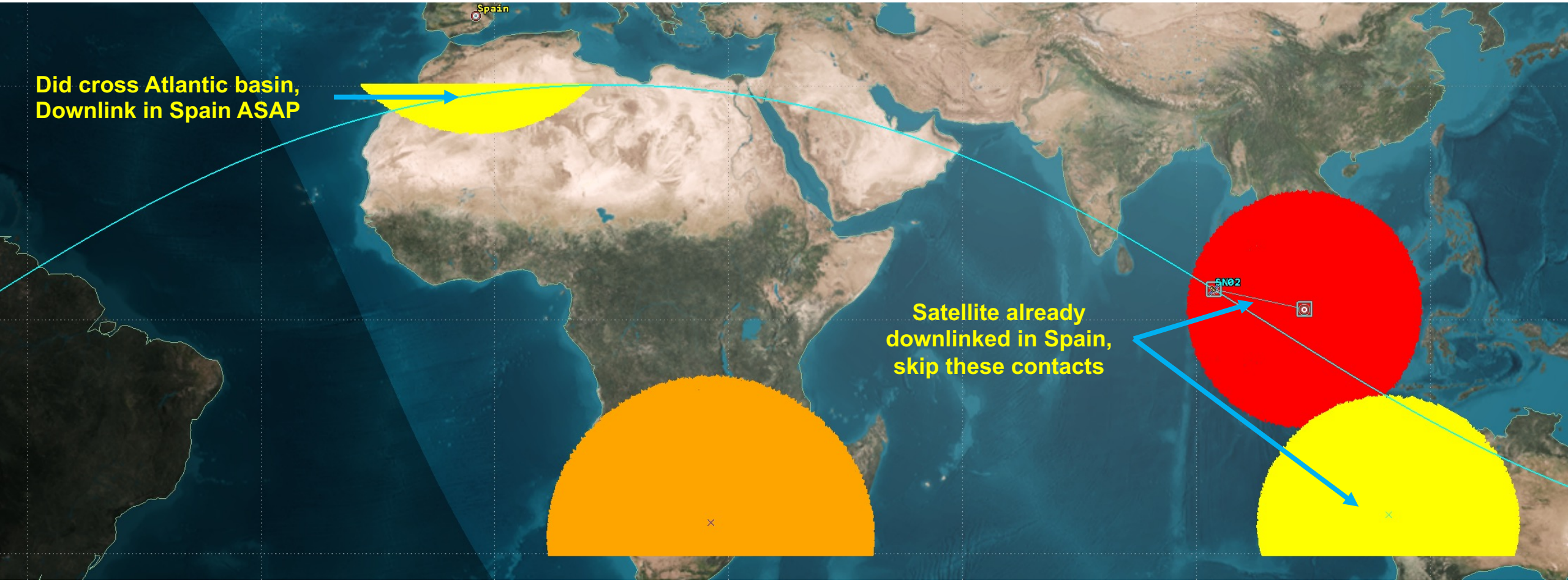
Data Products

- **NRT data access**
  - **Work with the entire NRT community to ensure data formats (BUFR, NetCDF) conform to meet requirements**
  - **Ensure NRT users are being provided with the data products *they* want (L1 vs L2)**
- **Level 2 data products**
  - **The Low Latency demo only processed Level 1 data products**
  - **Test L2 algorithms with variable size data products from the Low Latency demo (in progress)**
  - **Improve speed for L2b (specifically AVTMP)**
    - **MIRS requires ancillary data contributing to the long runtime**
    - **MIT LL would like to use Neural Networks to improve AVTMP processing speed to ~5 minutes**

      Neural Network would *not* require ancillary data

Science Software	Level	Runtime [min:sec]	Notes
Unified Resolution	L2a	00:17	
Atmos. Vert. Temp. & Moisture Profiles	L2b	46:00	Investigating MITLL Neural Network
Inst. Surf. Rain Rate	L2b	03:23	
TC Intensity - TCIE	L2b	09:19	May not be needed for NRT


Did not cross Atlantic basin
Satellite did not cross the Atlantic Basin, skip this contact
NO2


Spain
Did cross Atlantic basin,
Downlink in Spain ASAP
SN02
Satellite already
downlinked in Spain,
skip these contacts