Exploring Instrument Hosting Potentials from Emerging Internet Platforms

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Acknowledgement

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College Park, MD Feb 19 2020

Emerging Internet Platform


Alphabet Loon:
Began since June 2013


Space-X StarLink:
First launch on 24 May 2019

OneWeb:
First launched on 27 February 2019

- ☐ Mainly purpose for internet connection
- ☐ Better spatial and temporal coverage ➔ similar requirements for weather satellites
- ☐ Providing host opportunities for future satellite sensors

NOAA Technology Maturation Program (TMP)

Techology Maturation Program: Scope

Aligning emerging technology with NOAA's needs is the first step in the technology maturation process. Two things are needed for an emerging technology to be a good candidate for NOAA TMP support. First, the technology must have a clear relevance to a possible NOAA observing system. Second, the technology must lack the funding resources to be matured in a timely fashion as needed by NOAA.

Satellites and instruments used for collecting environmental information at NOAA are often large and expensive. TMP addresses this issue by seeking capabilities to produce smaller, more efficient satellites and instruments. TMP aims to demonstrate that these miniaturized systems can accomplish a vital task: collecting our nation's weather data. To accomplish this goal, TMP is exploring how smaller and simpler technology can contribute to NOAA's mission, and optimize existing systems and future projects that have already been approved.

◁ Read about TMP's objectives | Read about TMP's partners ▷

Evolution of the TIROS weather satellite series from 1960 to 1986. (Image credit: NOAA)

https://www.nesdis.noaa.gov/OPPA/tmp-faqs.php

- **Project Name: Hosted Payloads Study**
- **Project ID: TMP 18-11**
  - Explore payload hosting opportunities (near-space and space-based)
  - Match sensor capability to payload capacities
  - Simulate constellations of sensors and evaluate benefit to NOAA applications

Content

- Loon internet platform
  - Flight dynamics, measurements, hosting capability
  - Loon potentially-hosted instrument simulations
    - Passive MW or GPS RO instrument
  - OSSE experiment evaluations (GPS RO instrument)

- Extending space internet platform
  - Space-X Starlink Platform

- Concluding remarks

Google Loon Overview

Project Loon is a network of stratospheric balloons, designed to extend Internet connectivity to people in rural and remote areas worldwide

Auto launchers: capable of safely and consistently launching a new balloon every 30 minutes.

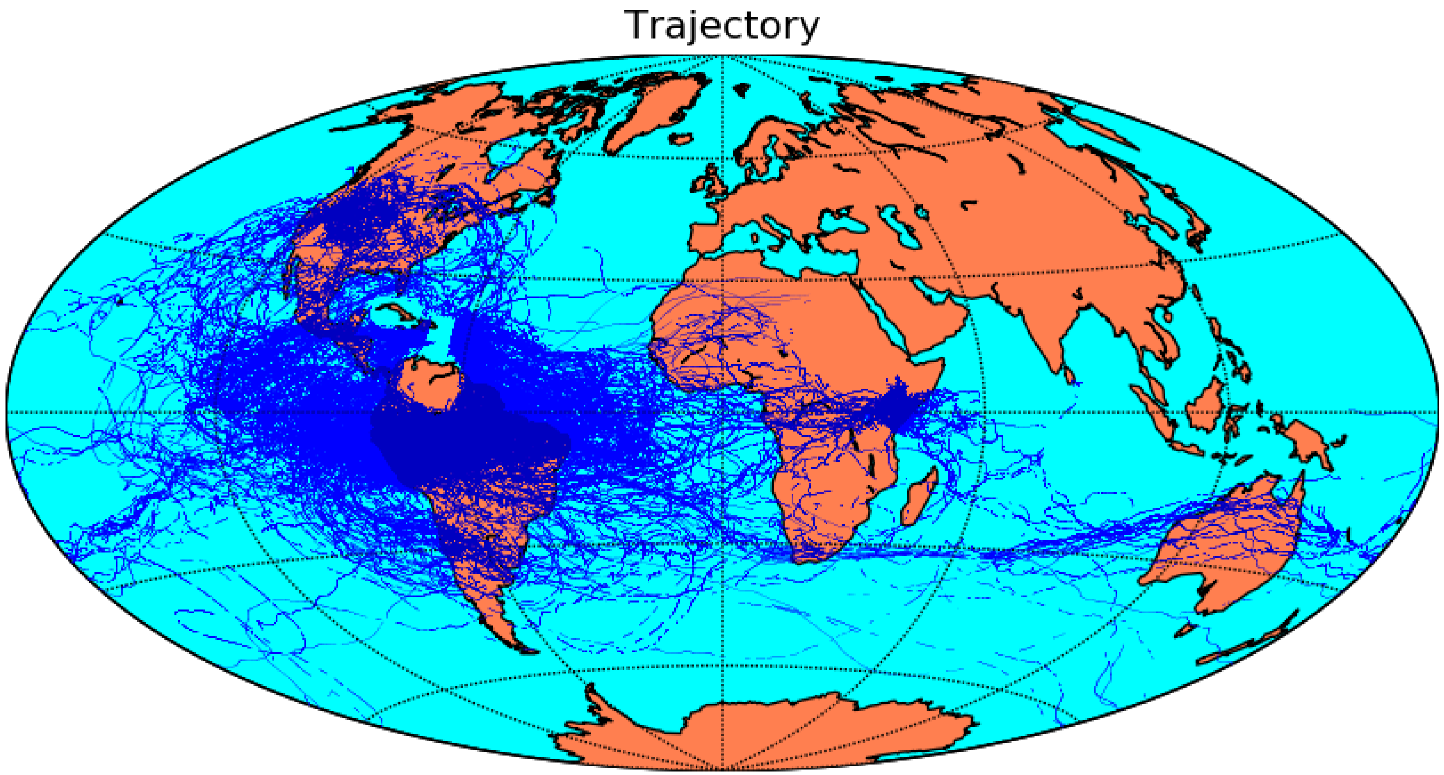
Status: over 25 million km of test flights since the project began. Duration: up to 190 days in the stratosphere.

Made from sheets of polyethylene, each tennis court-sized balloon is built to last for well over 100 days before landing back on Earth in a controlled descent. Standing 15 m (49 ft) across and 12 m (39 ft)

Flight equipment's: Solar panel system, antenna, flight capsule, parachute

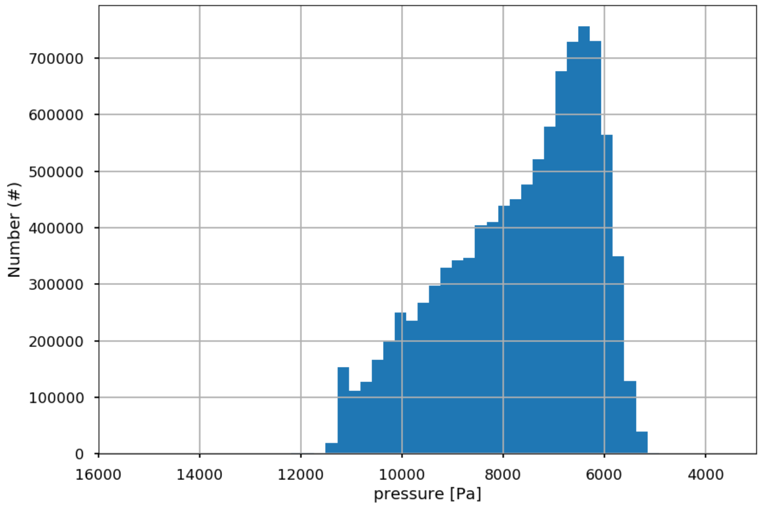
from https://loon.co/

Google Loon Trajectory Patterns (2016 -2017)

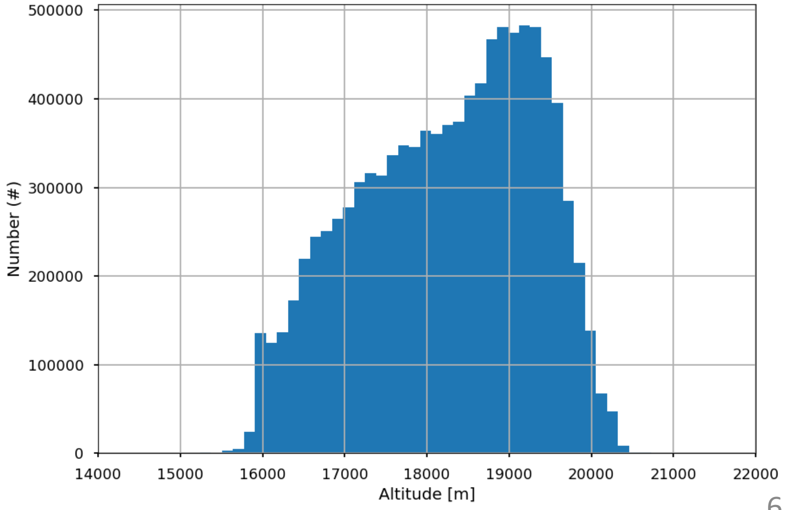


Flight Trajectory in 2016-2017

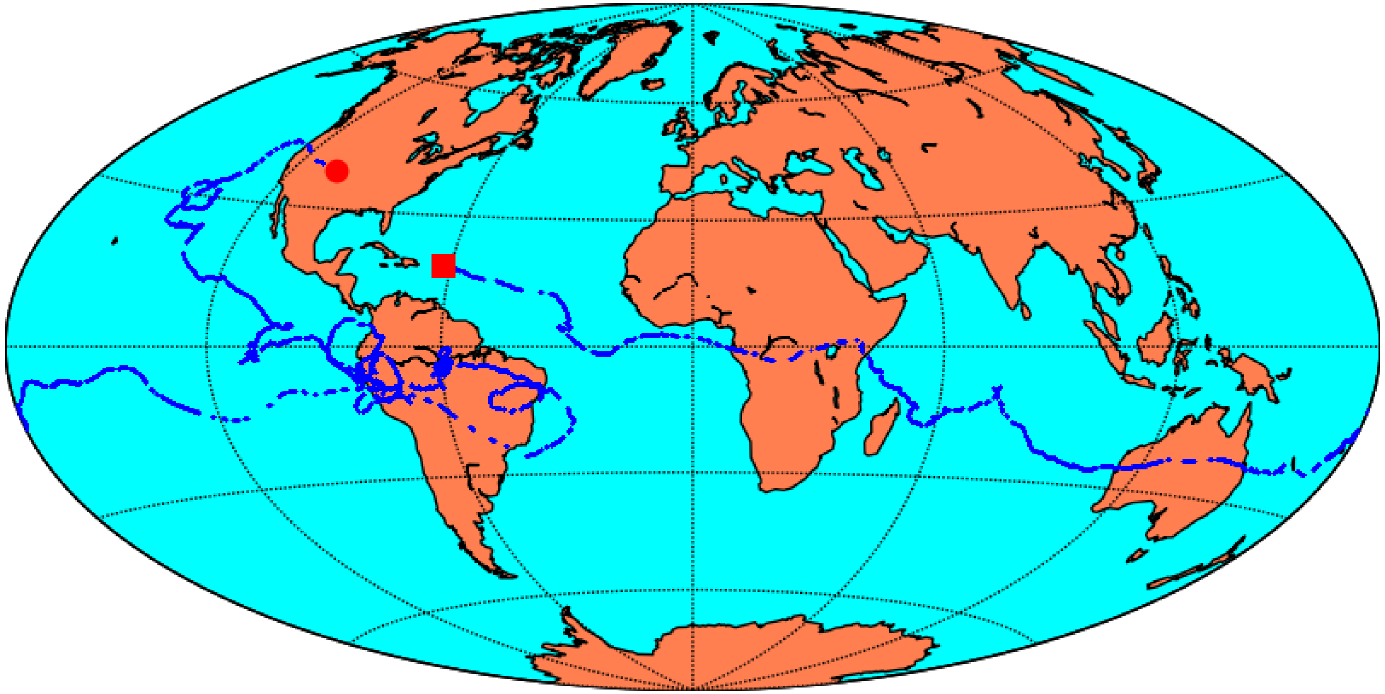
Pressure Distribution



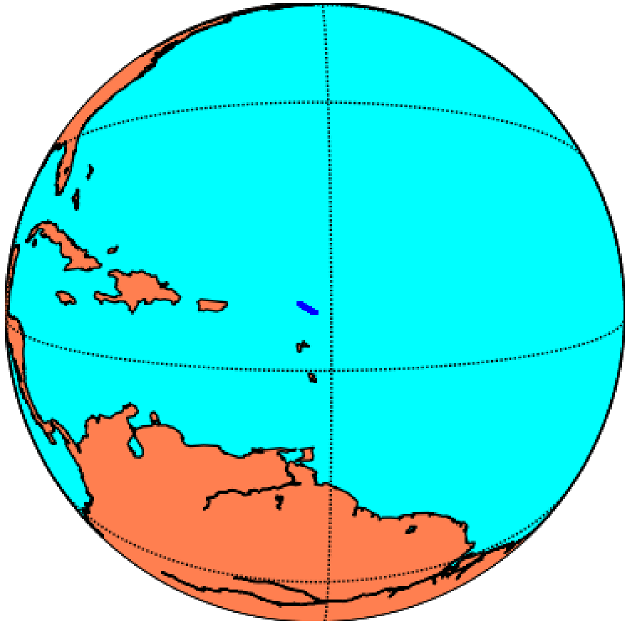
Altitude Distribution



Longest Flight
2017/04/17 – 2017/10/08



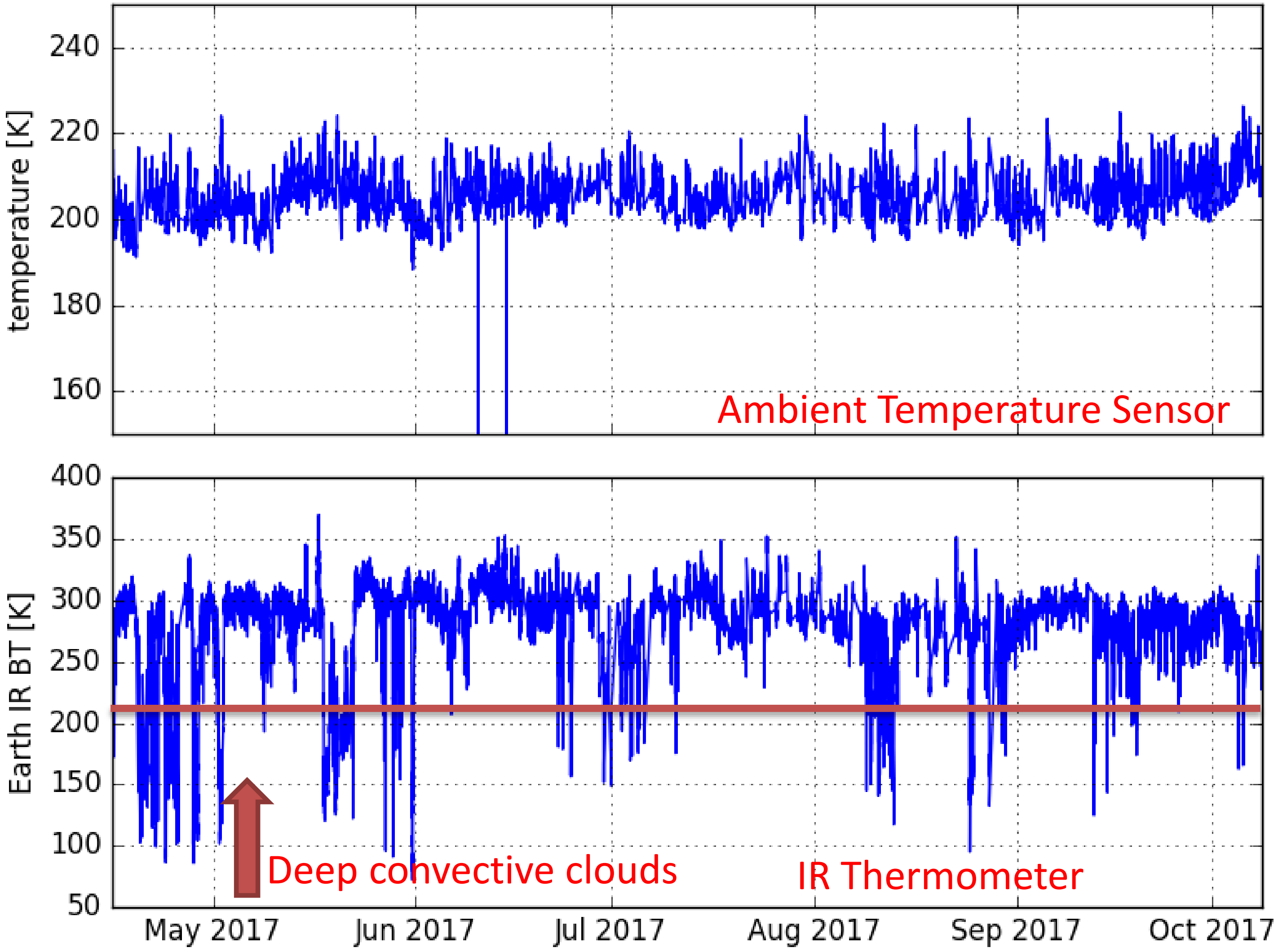
flight ID 16245112693274640384



2017-04-15T13:24:43 at 1000 km above earth

Loon Measurement Capability

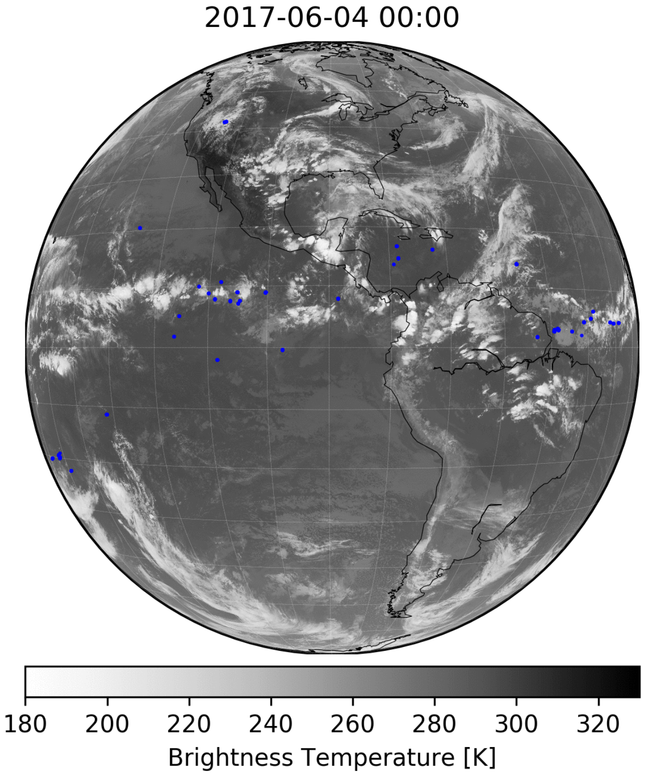
Variables	Measurement	Units	Uncertainties
Winds	Derived from GPS positions	m/s	±2.5 m
Ambient Pressure	Pressure Sensor	hPa	± 1.0 hPa
Ambient Temperature	Temperature Sensor	°C	± 5°C day ± 2°C night
Earth IR Flux	IR Thermometer IR flux = 0.000000056704*T^4	W/M^2	± 6°C for

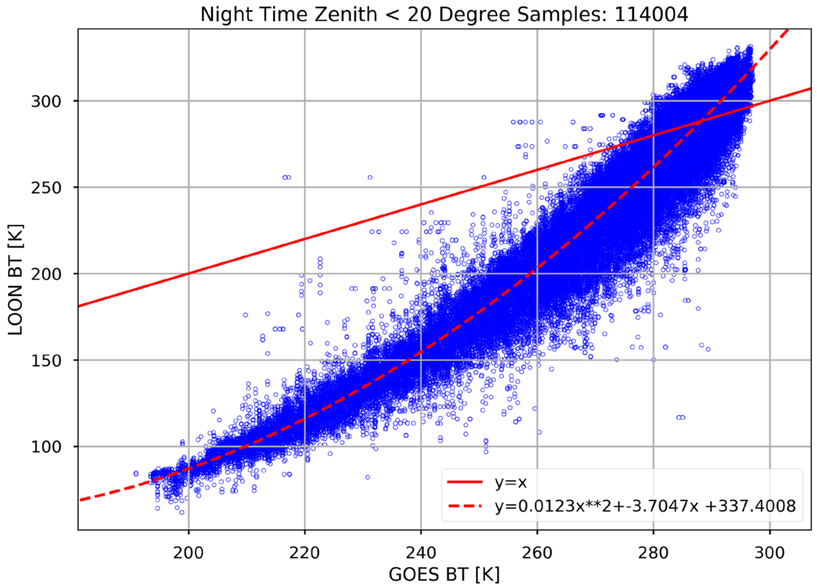


GOES-16 ABI *vs.* Loon IR Flux Measurements

ABI on GOES16

Melexis MLX90614 IR Thermometer on Google Loon

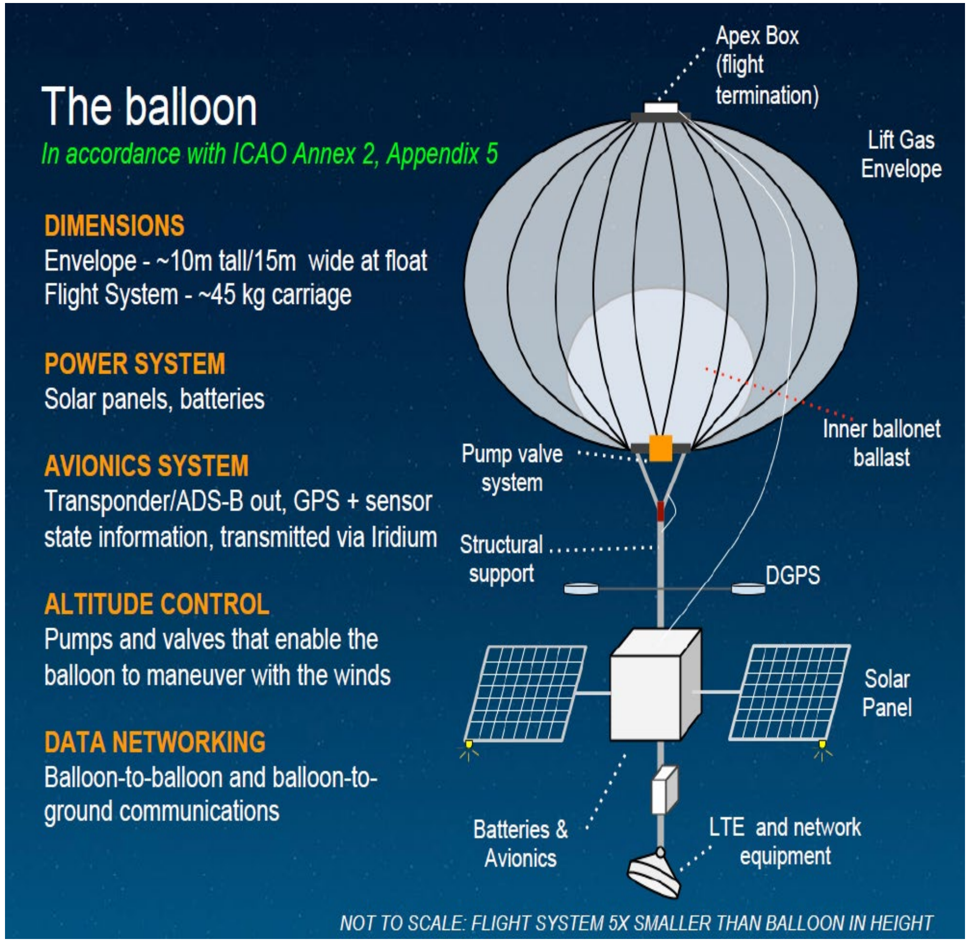




- Relationship is clear
- Nighttime is more stable (less uncertainties)
- quantitatively do not match (need further improve and understand Loon IR sensors)

Loon Platform Characteristics

- Solar power
  - 100 Watts of power
  - Rechargeable battery (day and night)
- Stratosphere environment
  - High altitudes between 18 km and 25 km:
  - Minimal turbulence
  - Large diurnal cycles (~ 30K)
- Payload capacity - Available on Loon platform
  - Mass: 12 kg
  - Volume: 20 X 20 X 25 cm^3
  - Power: 60 Watts
  - Data downlink 1Gb/Second (memory device onboard available)
- Platform stability
  - Active yaw control: 7 degree 95th percentile error, over 95 percent of all 5-minute time windows.
  - Passive pitch and roll control with typical error of +/- 2 degrees.
  - The roll, pitch, and yaw angles are measured by attitude sensors with the accuracy of +/- 0.5 deg.
- Point-to-point navigation and persistent flight
  - 100 days lifetime
  - Launches are largely automated. Capable of launching balloons every 30 minutes
  - Pinpoint landing with recoverable payloads



The balloon

In accordance with ICAO Annex 2, Appendix 5

DIMENSIONS

Envelope - ~10m tall/15m wide at float

Flight System - ~45 kg carriage

POWER SYSTEM

Solar panels, batteries

AVIONICS SYSTEM

Transponder/ADS-B out, GPS + sensor state information, transmitted via Iridium

ALTITUDE CONTROL

Pumps and valves that enable the balloon to maneuver with the winds

DATA NETWORKING

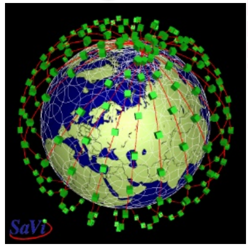
Balloon-to-balloon and balloon-to-ground communications

NOT TO SCALE: FLIGHT SYSTEM 5X SMALLER THAN BALLOON IN HEIGHT

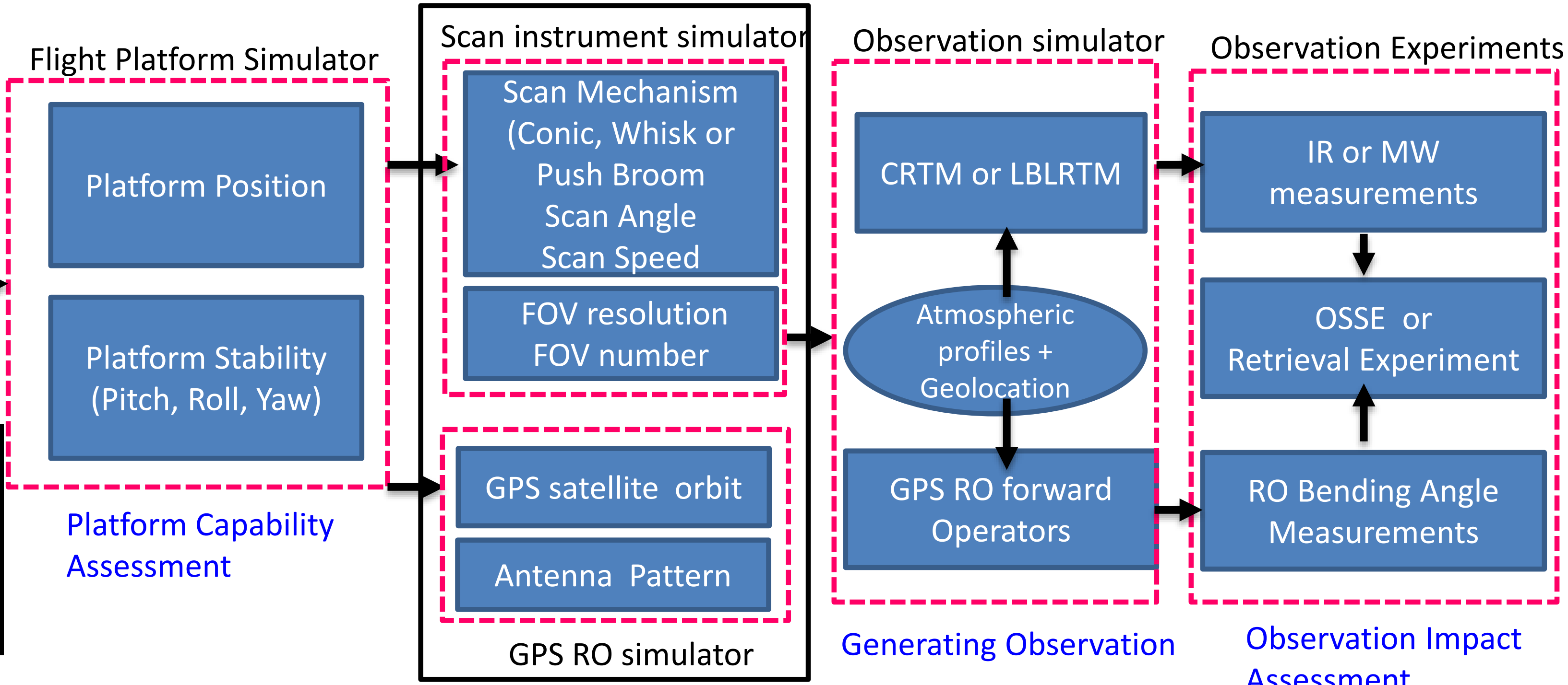
https://www.icao.int/SAM/Documents/2016-CRPP4/Peru%20GREPECAS%20PPRC-4%20brief%20Jul%2016.pdf

Payload Simulation System

From trajectory model
or real data



From SGP4 model
with orbit parameters



Flight Platform Simulator

Platform Position

Platform Stability
(Pitch, Roll, Yaw)

Platform Capability
Assessment

Scan instrument simulator

Scan Mechanism
(Conic, Whisk or
Push Broom
Scan Angle
Scan Speed

FOV resolution
FOV number

GPS satellite orbit

Antenna Pattern

GPS RO simulator

Generating Observation Location

Observation simulator

CRTM or LBLRTM

Atmospheric
profiles +
Geolocation

GPS RO forward
Operators

Generating Observation

Observation Experiments

IR or MW
measurements

OSSE or
Retrieval Experiment

RO Bending Angle
Measurements

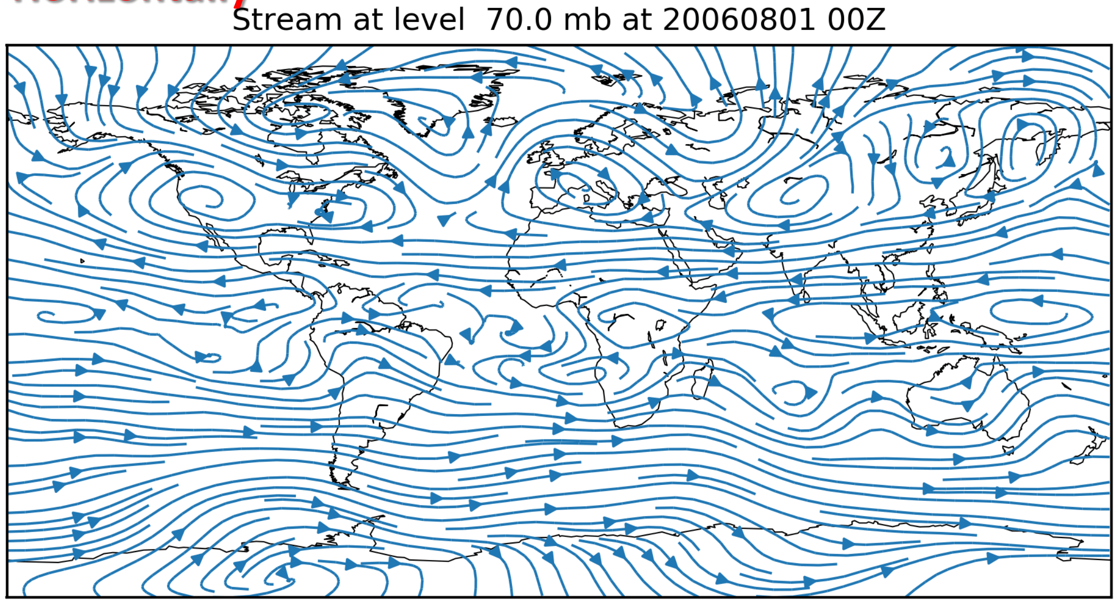
Observation Impact
Assessment

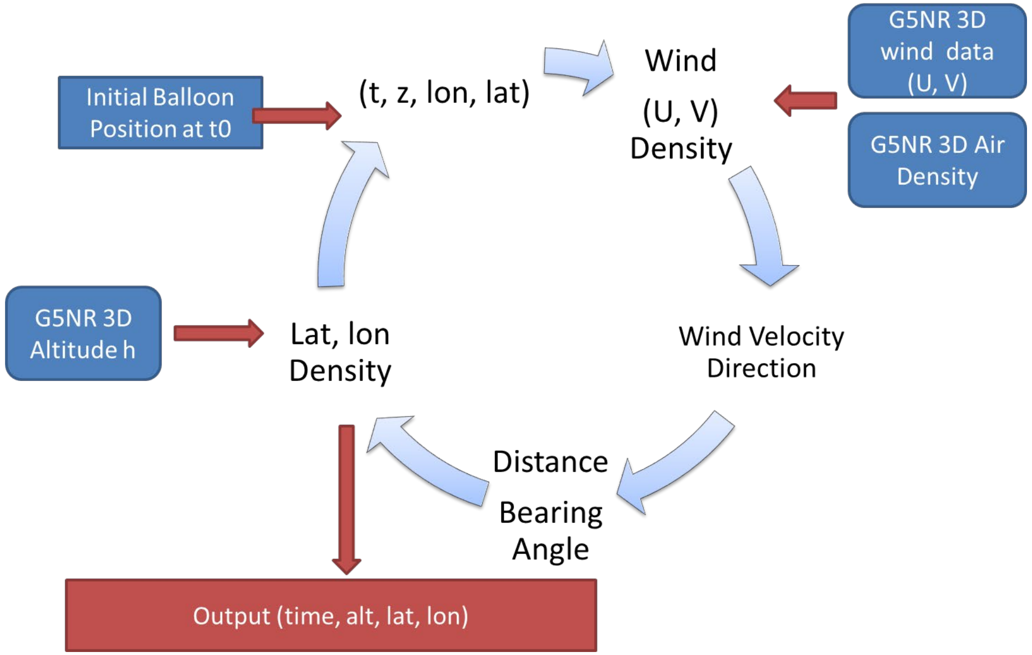
Candidate sensors on near-space platforms **– Microwave Sounders** and **GPS RO sensors**

Simple Balloon Trajectory Model

Vertically

Horizontally



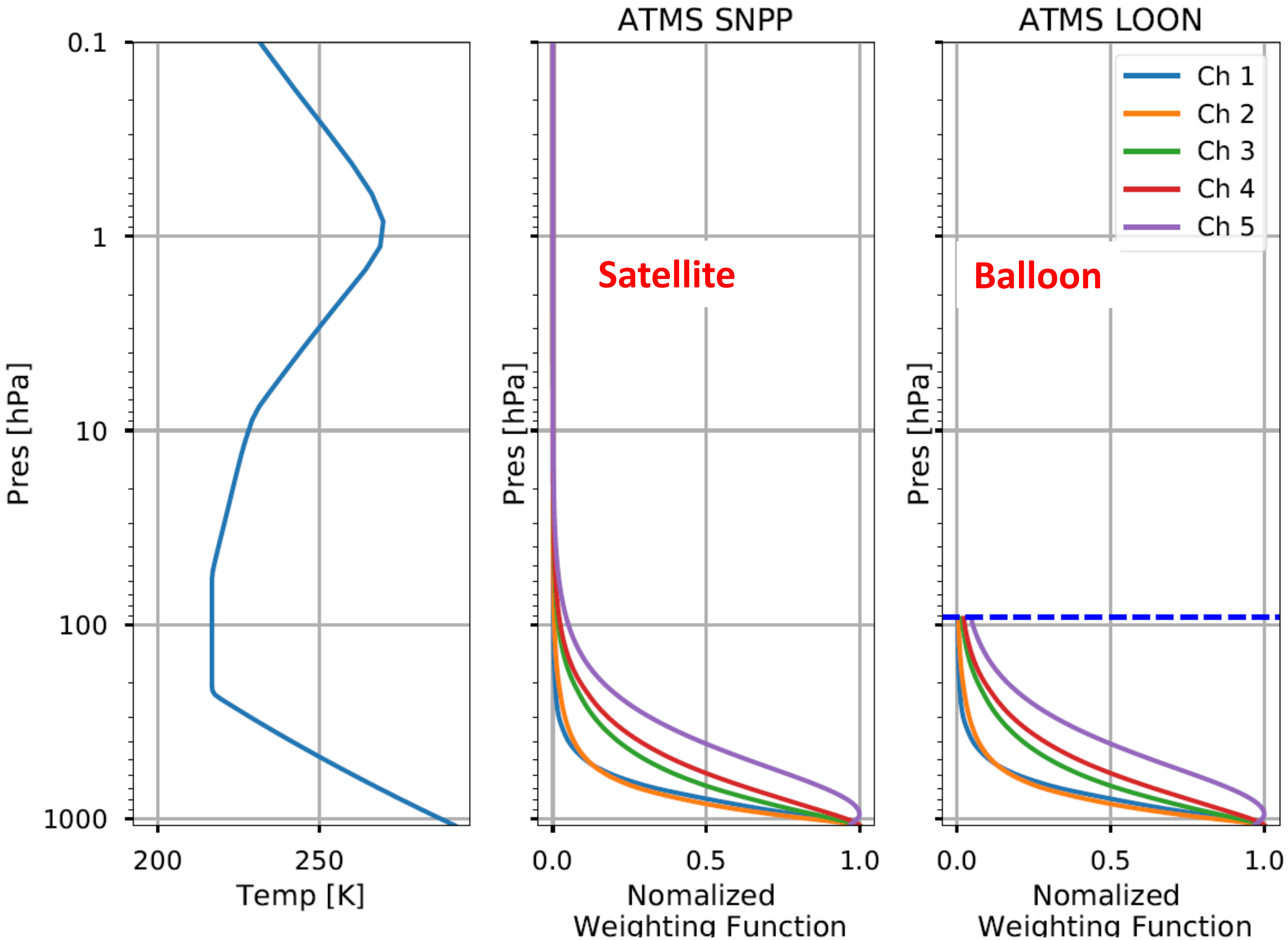


Horizontally: Assuming an ideal, infinitely small air parcel, the trajectory can be defined by the differential trajectory equation:

$$\frac{d\vec{X}}{dt} = \vec{V}\left(\vec{X}(t), t\right)$$

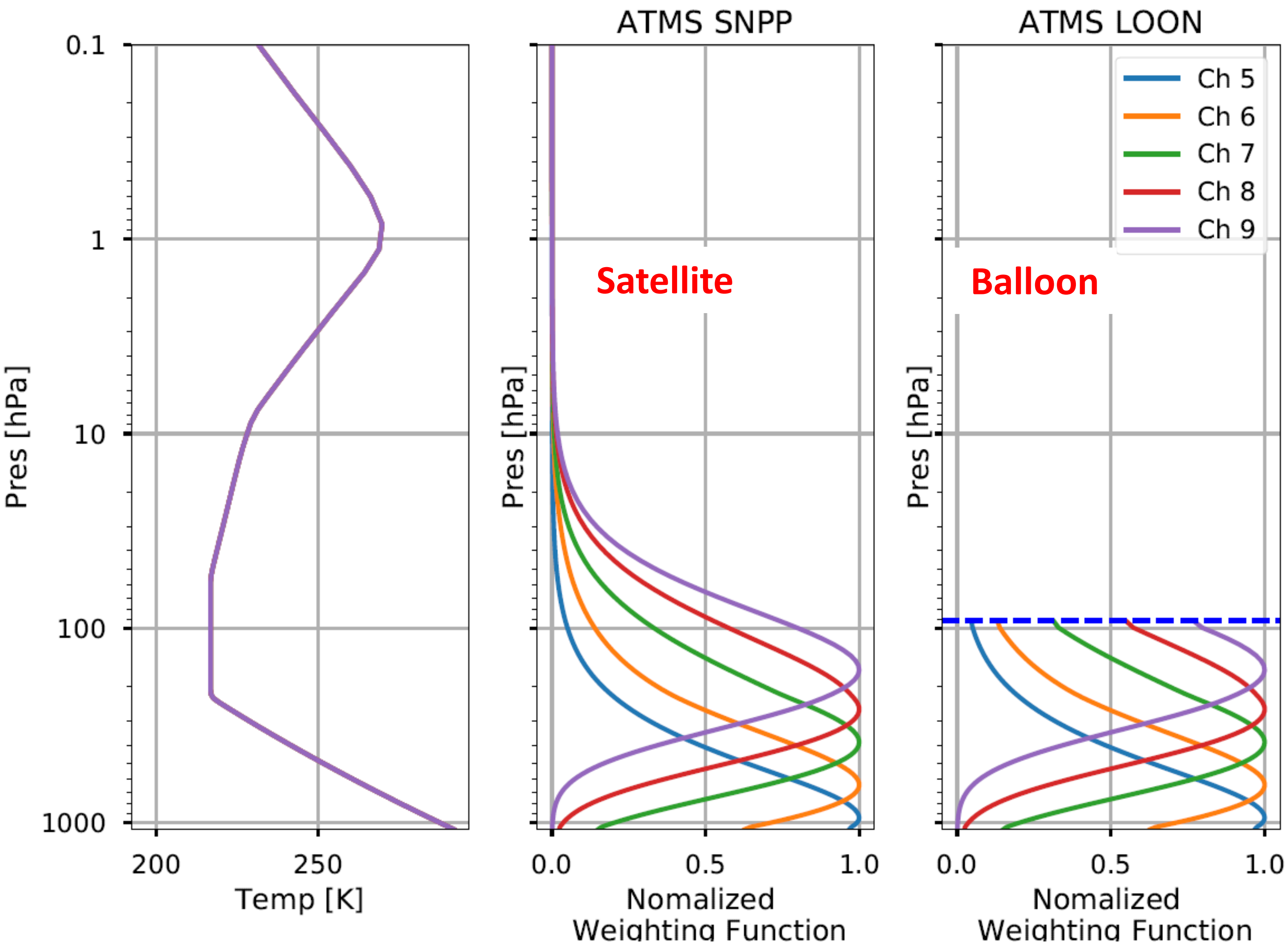
Vertically: Superpressure balloons have a constant volume and thus are constrained to stay on isopycnic surfaces (cannot follow the vertical motions of air parcels)

CRTM simulated ATMS Ch1-5 Loon Platform vs Satellite Platform



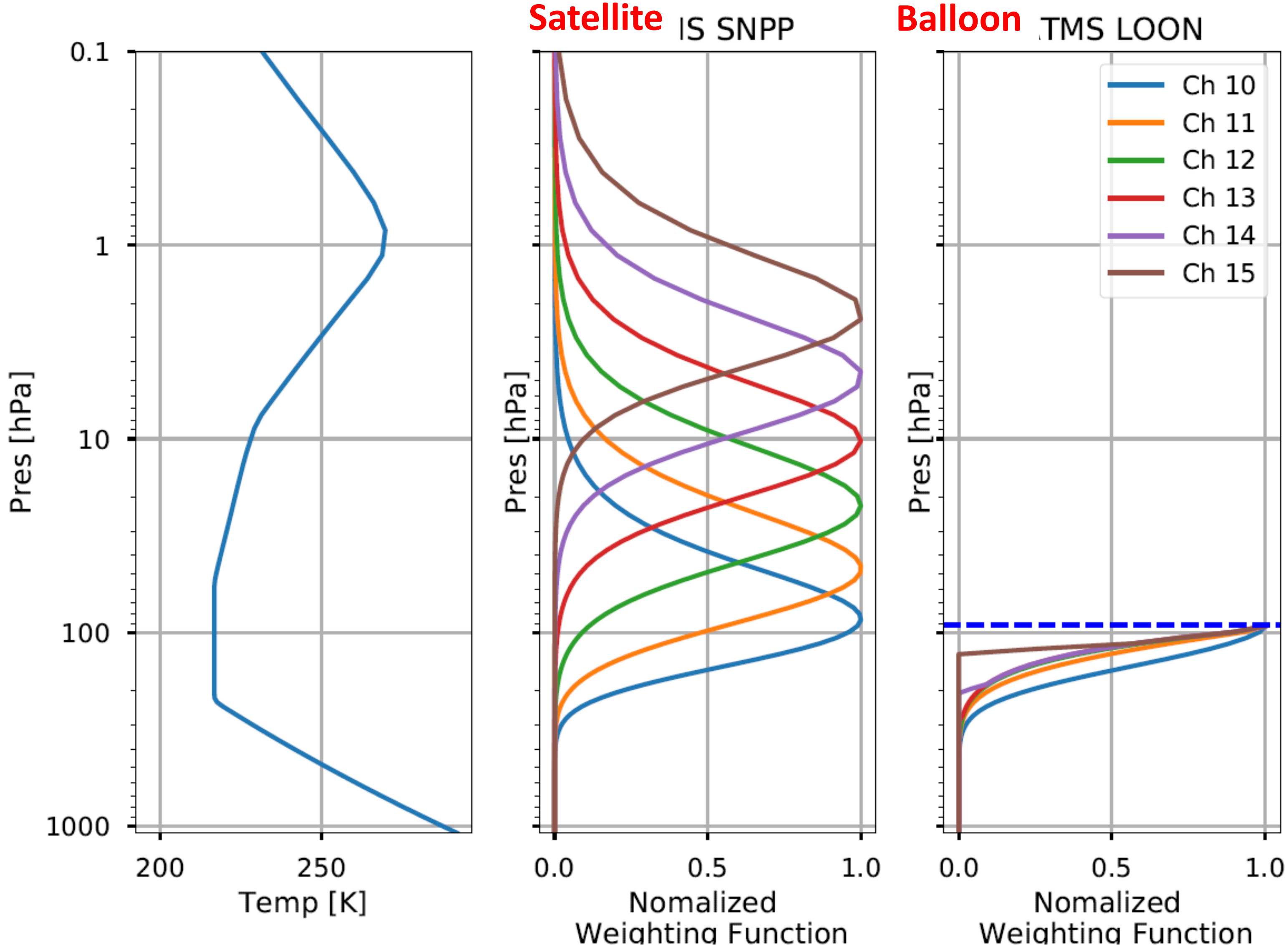
Window – water vapor or surface emissivity

CRTM simulated ATMS Ch5-9 Loon Platform vs Satellite Platform



Lower Sounding channels

CRTM simulated ATMS Ch10-15 Loon Platform vs Satellite Platform

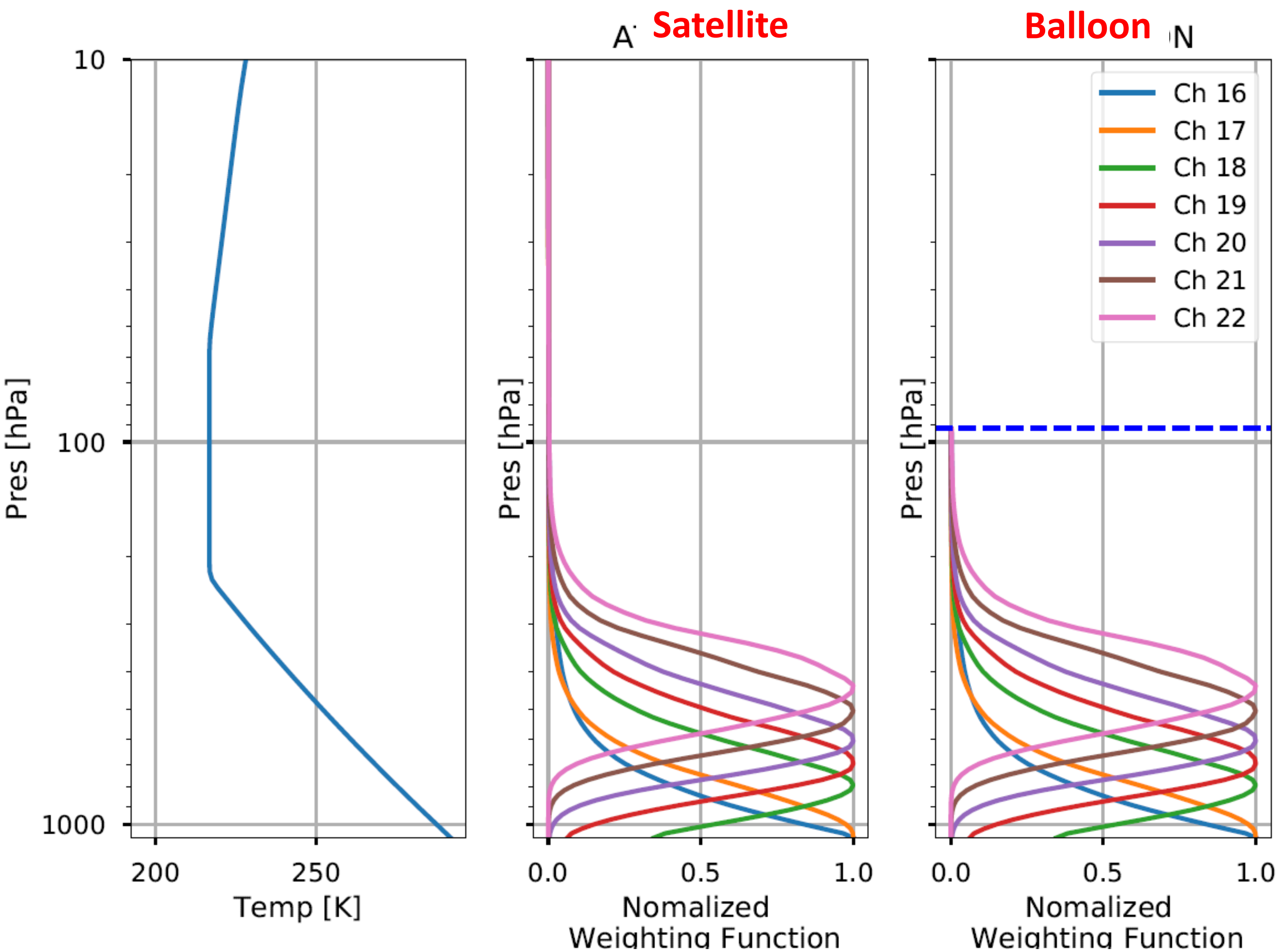


Satellite

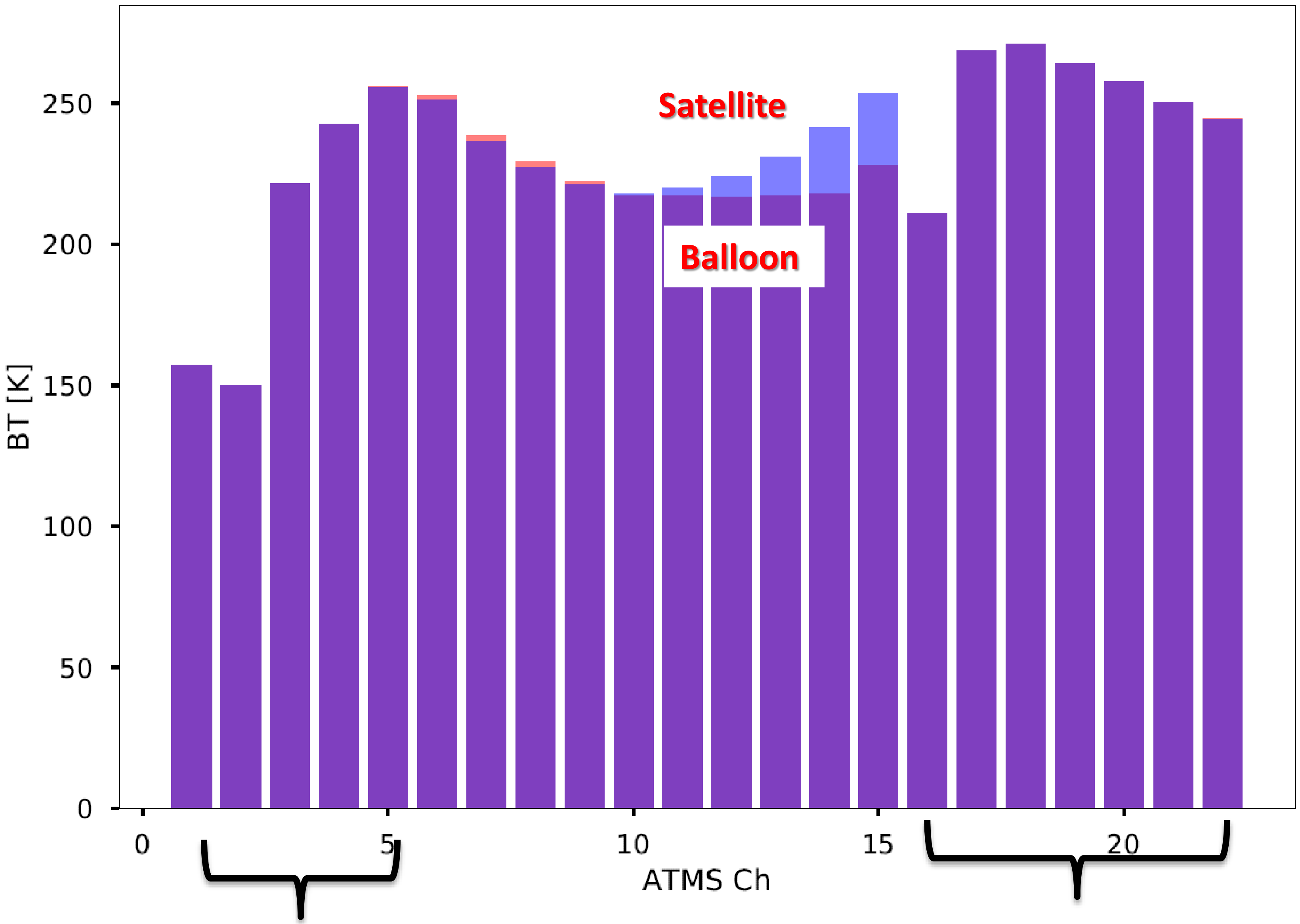
Balloon

Upper Sounding channels

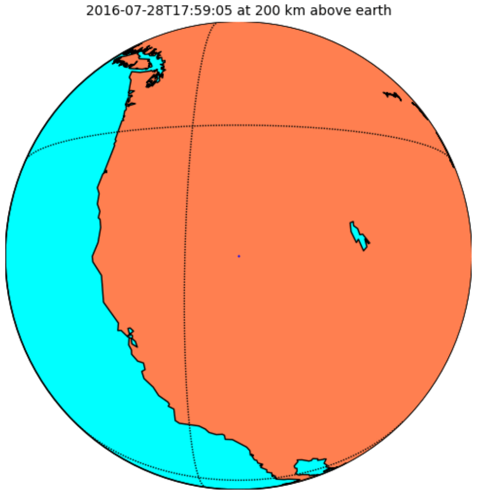
CRTM simulated ATMS Ch16-22
Loon Platform vs Satellite Platform



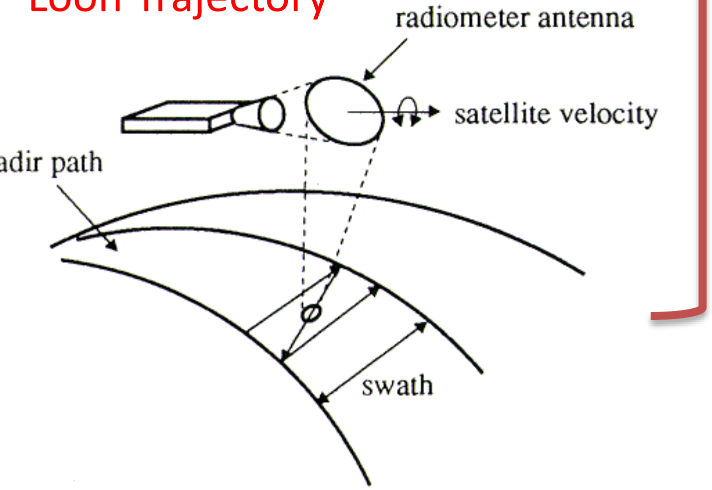
Simulated ATMS Brightness Temperature
Balloon vs Satellite



Simulating ATMS-like Scan Instruments

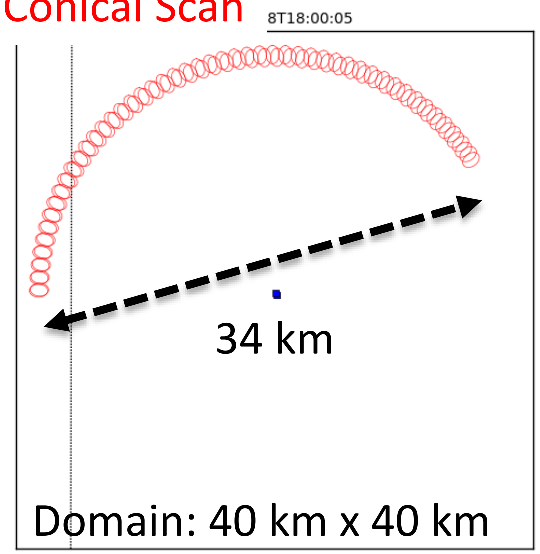


Loon Trajectory

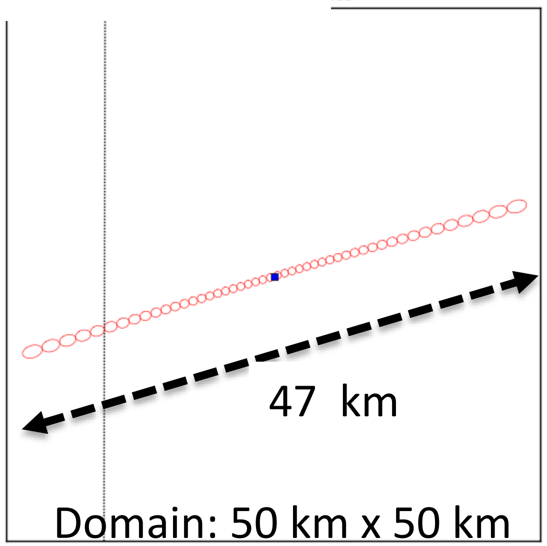


Scan Mechanism

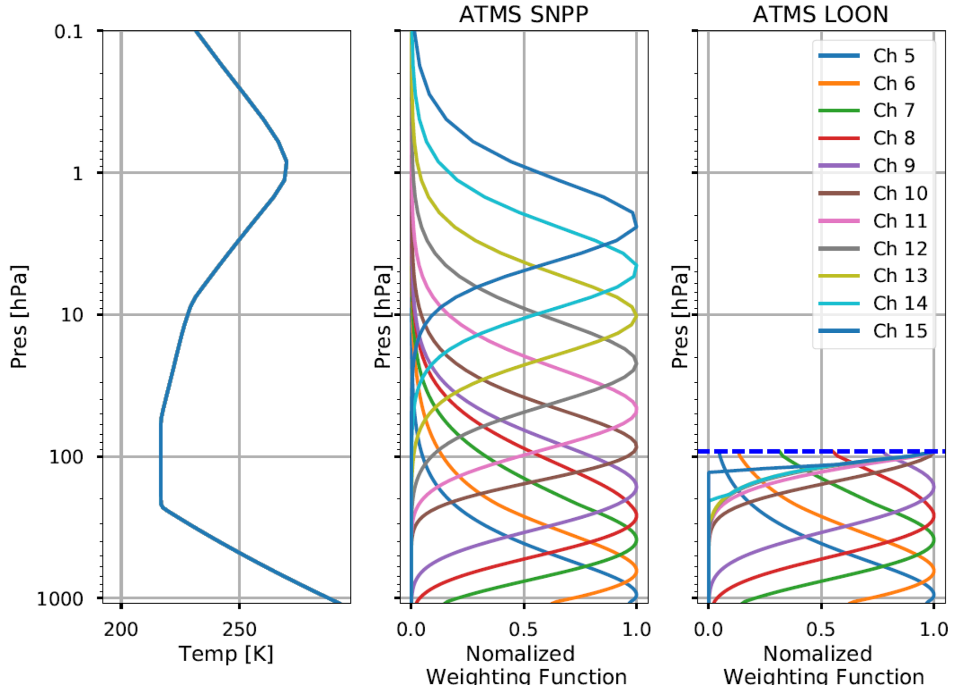
Conical Scan



Cross-track scan



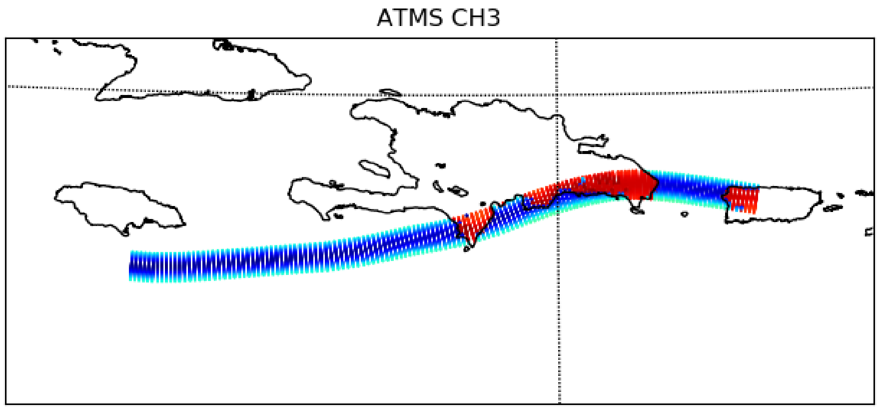
CRTM

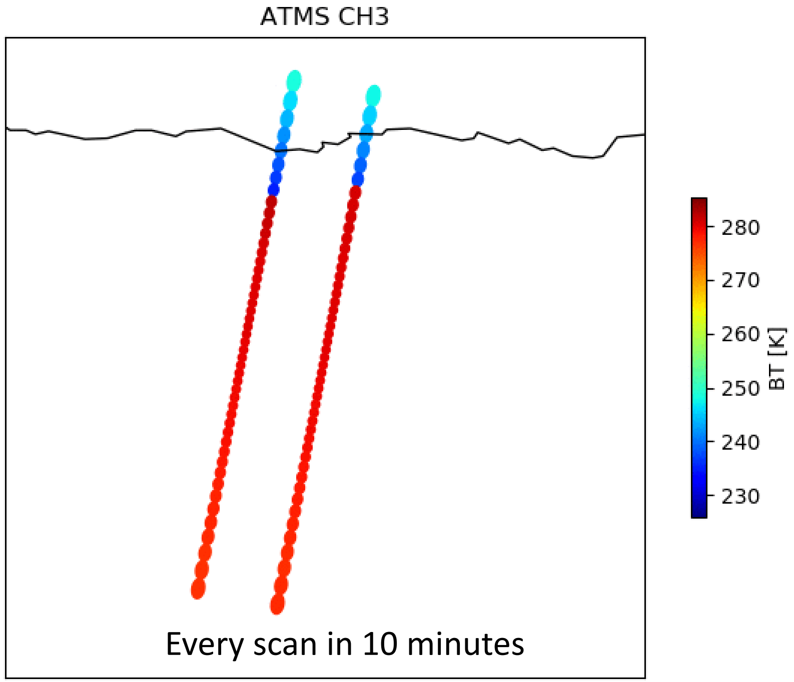


Balloon Based MW Observations

Example ATMS-LX simulation

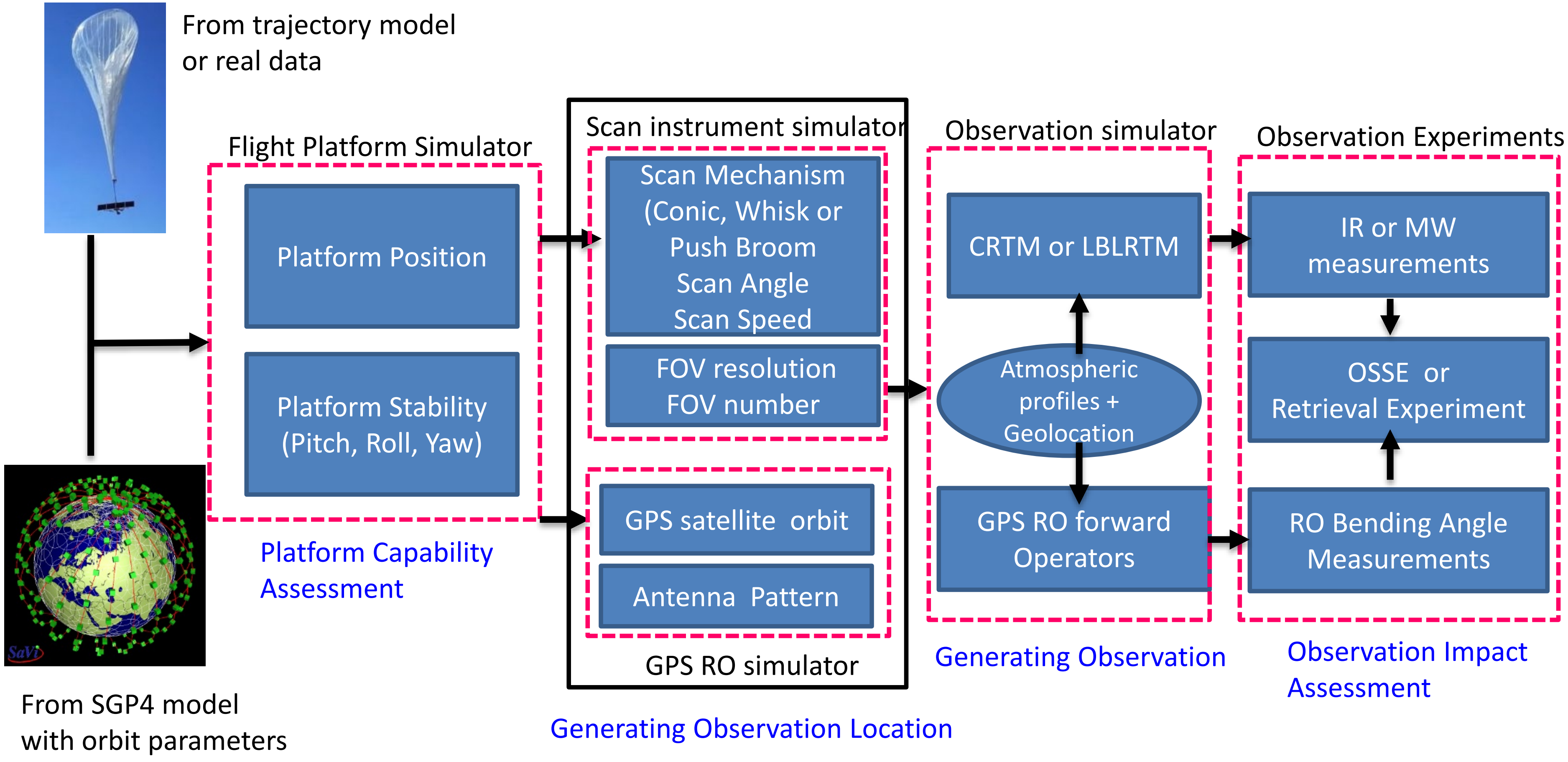
- ATMS-LX was applied to the payload simulator using available Loon flight information
- ATMS-LX geolocation/geometry information was input into satellite simulate (Community Global OSSE Package) using G5NR and CRTM
- Although CRTM forward operator works in “aircraft” mode, TL and AD need to be developed to assess in physical retrieval/data assimilation
- Potential applications could be demonstrated through deployment of balloons/ATMS-LX to monitor/predict severe weather, or tropical cyclones


ATMS CH3


ATMS CH3

Every scan in 10 minutes

Payload Simulation System



From trajectory model
or real data

From SGP4 model
with orbit parameters

Flight Platform Simulator

Platform Position

Platform Stability
(Pitch, Roll, Yaw)

Platform Capability
Assessment

Scan instrument simulator

Scan Mechanism
(Conic, Whisk or
Push Broom
Scan Angle
Scan Speed

FOV resolution
FOV number

GPS satellite orbit

Antenna Pattern

GPS RO simulator

Generating Observation Location

Observation simulator

CRTM or LBLRTM

Atmospheric
profiles +
Geolocation

GPS RO forward
Operators

Generating Observation

Observation Experiments

IR or MW
measurements

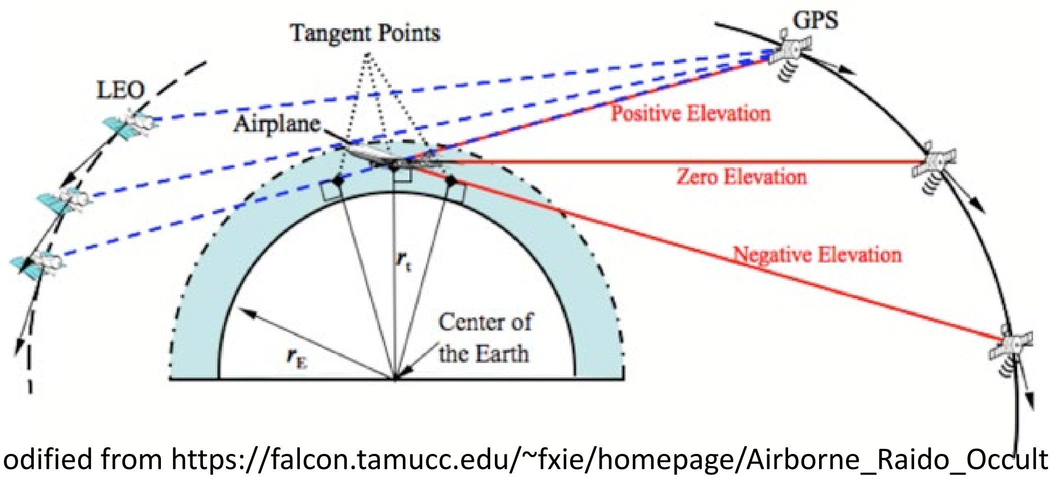
OSSE or
Retrieval Experiment

RO Bending Angle
Measurements

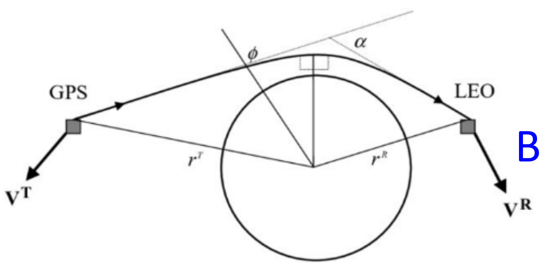
Observation Impact
Assessment

Candidate sensors on near-space platforms **– Microwave Sounders** and **GPS RO sensors**

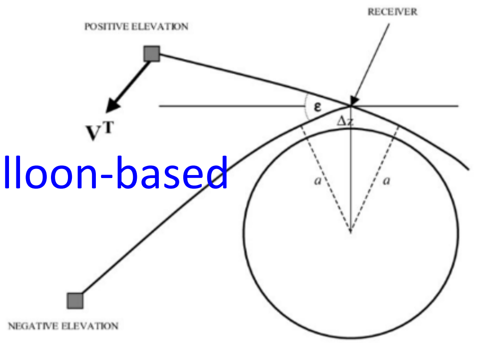
Satellite-based vs. Balloon-based GPS RO



Modified from https://falcon.tamucc.edu/~fxie/homepage/Airborne_Raido_Occultatio



Balloon-based



Bending angle

$$\alpha(a) = -2a \int_a^{\infty} \frac{\frac{d\ln n}{dx}}{(x^2 - a^2)^{1/2}} dx$$

Satellite-based

Positive elevation

$$\alpha_P(a) = -a \int_{n^R r^R}^{n^T r^T} \frac{\frac{d\ln n}{dx}}{(x^2 - a^2)^{1/2}} dx$$

Negative elevation

$$\alpha_N(a) = \alpha_P(a) - 2a \int_a^{n^R r^R} \frac{\frac{d\ln n}{dx}}{(x^2 - a^2)^{1/2}} dx$$

Partial Bending angle

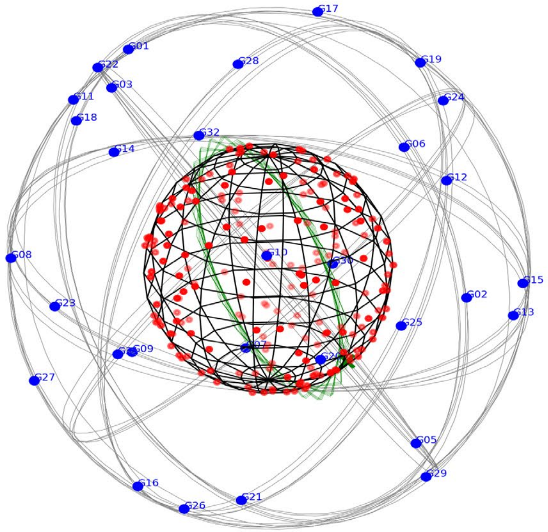
$$\alpha'(a) = -2a \int_a^{n^R r^R} \frac{\frac{d\ln n}{dx}}{(x^2 - a^2)^{1/2}} dx$$

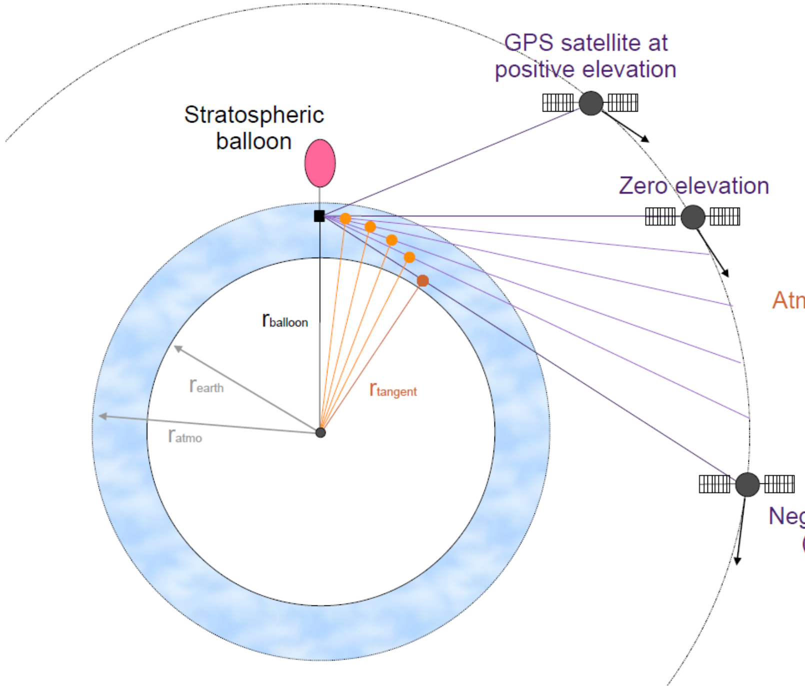
Healy et al. 2002: Abel transform inversion of radio occultation measurements made with a receiver inside the Earth's atmosphere. Annales Geophysicae (2002) 20: 1253–1256

- **Satellite–based GPS RO:**
  - The receiver outside the atmosphere
  - The receiver moves faster than transmitter
  - Bending angles with tangent heights extend from the lower atmosphere to the top
  - ROs occur globally
  - Smaller delta-x for slant path

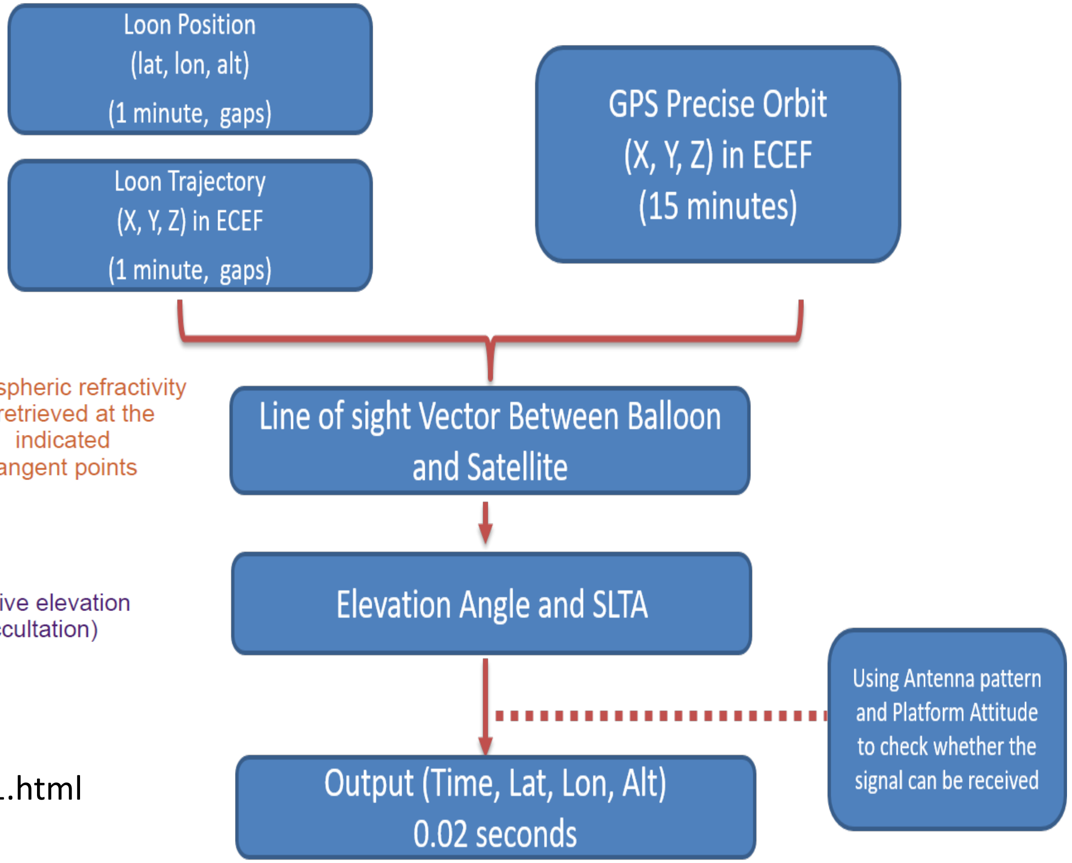
- **Balloon-Based GPS RO:**
  - Receiver outside the atmosphere
  - Transmitter moves faster than receiver
  - Partial bending angles with tangent heights below the receiver
  - ROs occur locally around the receiver
  - Larger delta-x for slant path

Balloon-based GSP RO Simulation





https://spotlight.unavco.org/station-pages/v191/v191.html



Loon Position
(lat, lon, alt)
(1 minute, gaps)

Loon Trajectory
(X, Y, Z) in ECEF
(1 minute, gaps)

GPS Precise Orbit
(X, Y, Z) in ECEF
(15 minutes)

Line of sight Vector Between Balloon and Satellite

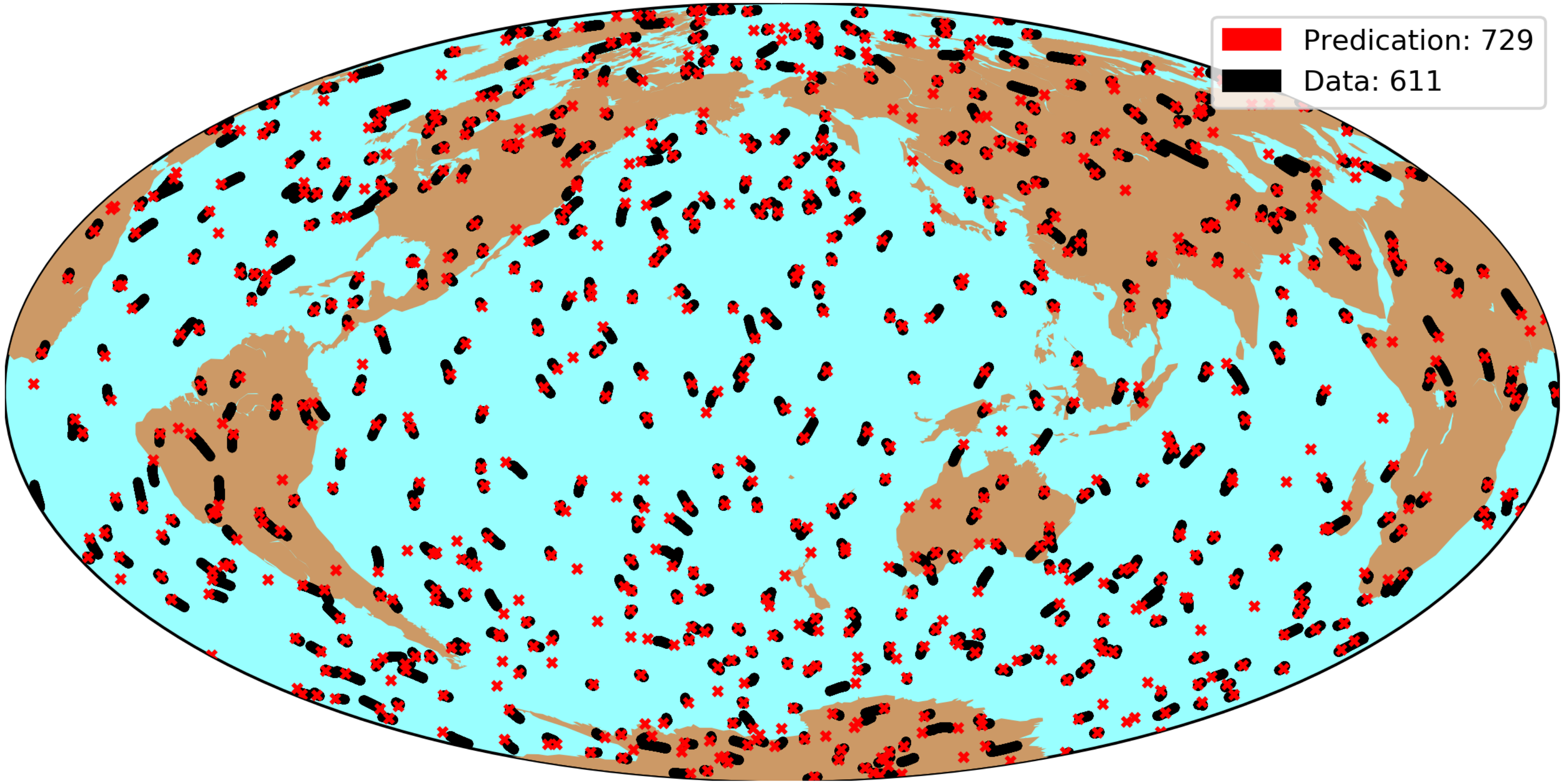
Elevation Angle and SLTA

Using Antenna pattern and Platform Attitude to check whether the signal can be received

Output (Time, Lat, Lon, Alt)
0.02 seconds

When and where GPS Radio Occultation is going to happen?

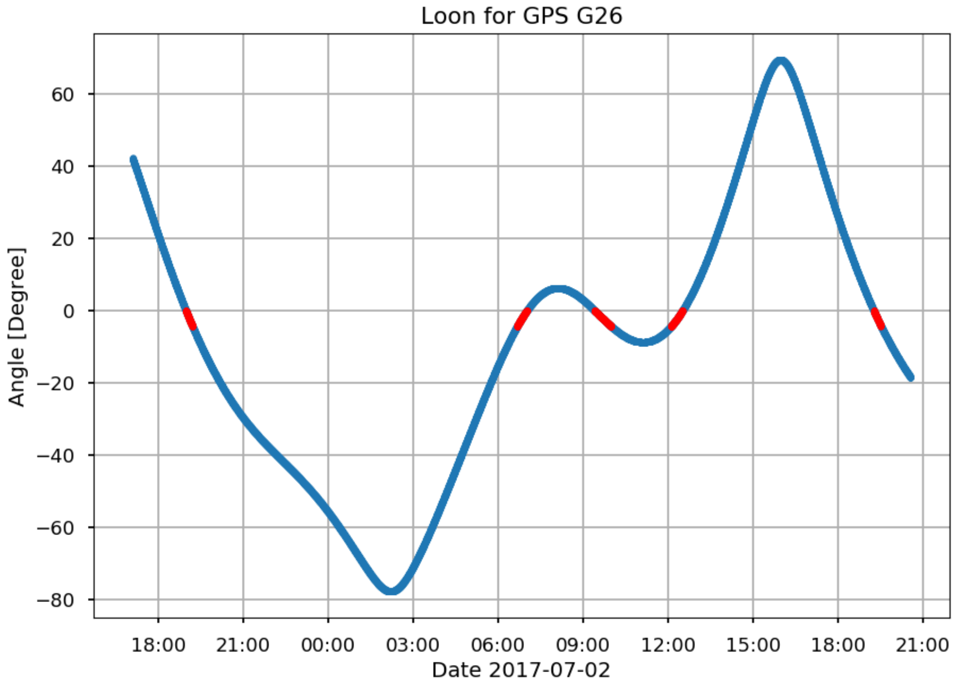
Validate RO prediction model: MetOp-B



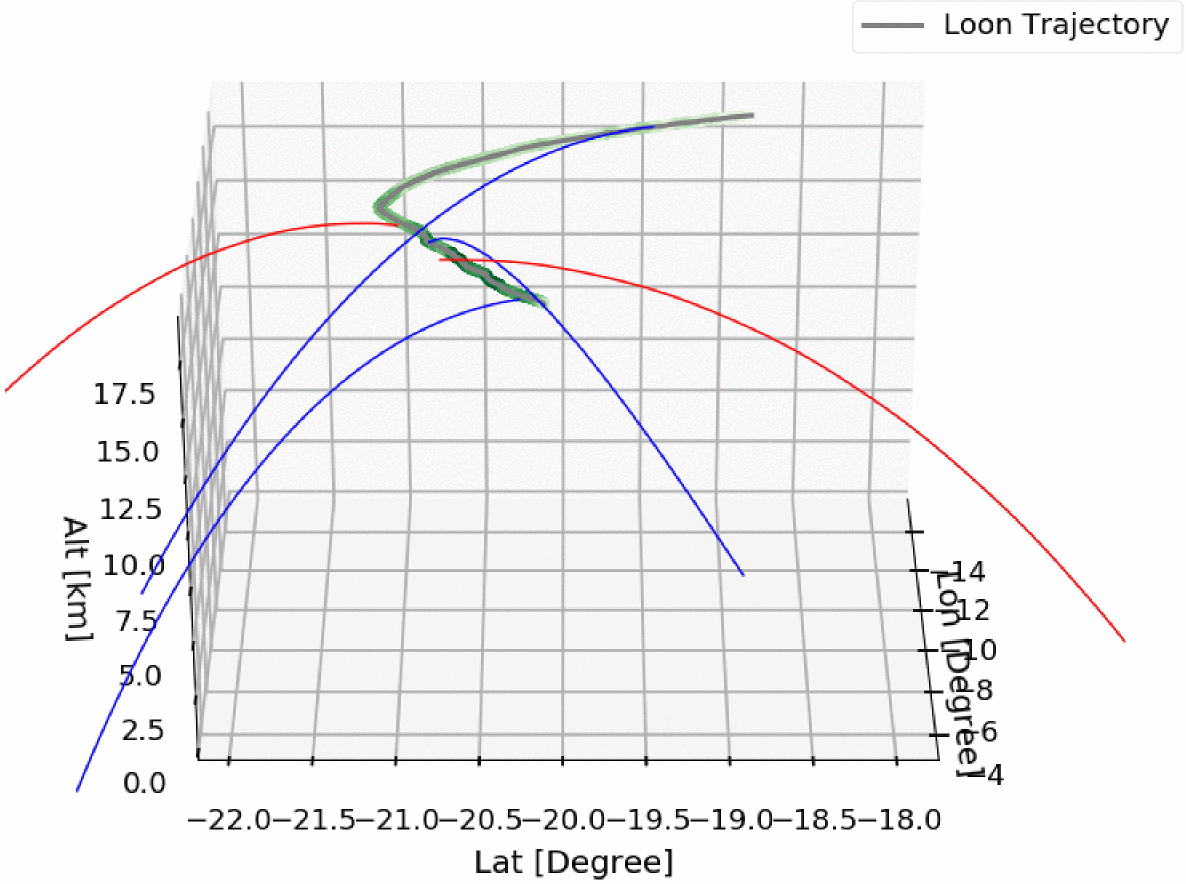
Predication model is based on perfect conditions. Actual GPS RO measurements are determined by the receiver and transmitter operational status.

Simulating GPSRO for the OSSE

GPSRO slant path for multiple occultation's, 1 balloon, 1 GPS transmitter



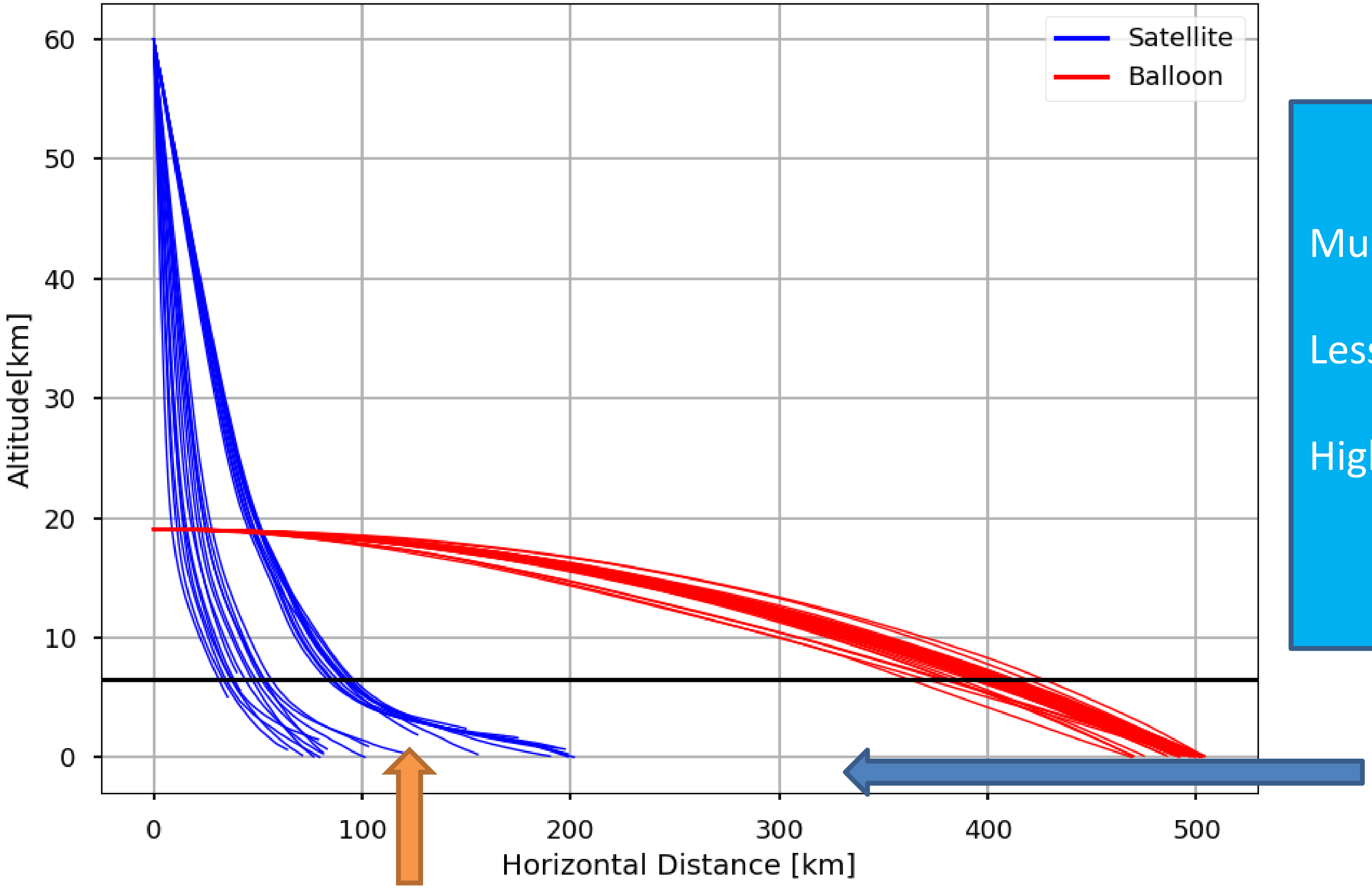
GPS evaluation angle varying with time



Red: GPS RO Tangent height Profile for rising case

Blue: GPS RO Tangent height Profile for setting case

Simulating GPSRO for the OSSE



Much larger delta-X

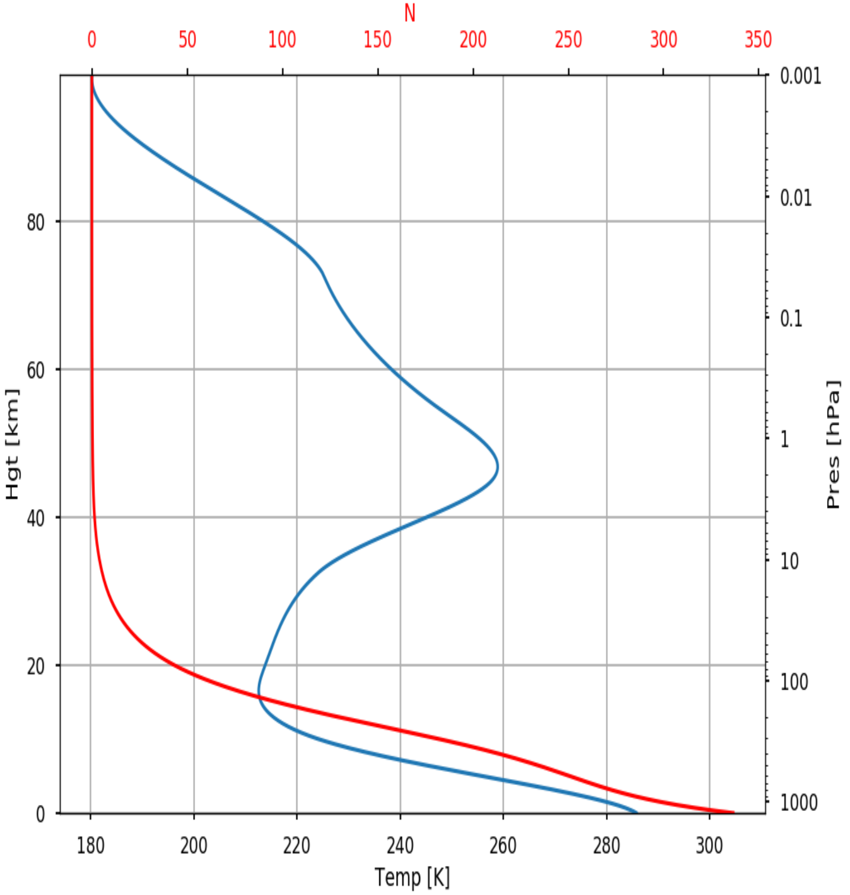
Less vertical coverage

Higher vertical resolution

Determined by azimuth angle where antenna received the signals

GPS RO Bending Angle Forward Operator (i)

$$N = (n-1)\times 10^6$$



$$N = k_1 \frac{P_d}{T} + k_2 \frac{e}{T^2} + k_3 \frac{e}{T}$$

Interpolate or Extrapolate Atmospheric Profiles along RO slant Path

Compute Refractive Index Profile
N

Compute Refractive Impact Factor
$x = n*(h+R_c)$

Compute differential Term

$$\frac{d\ln(n)/dx}{\sqrt{x^2-a^2}}$$

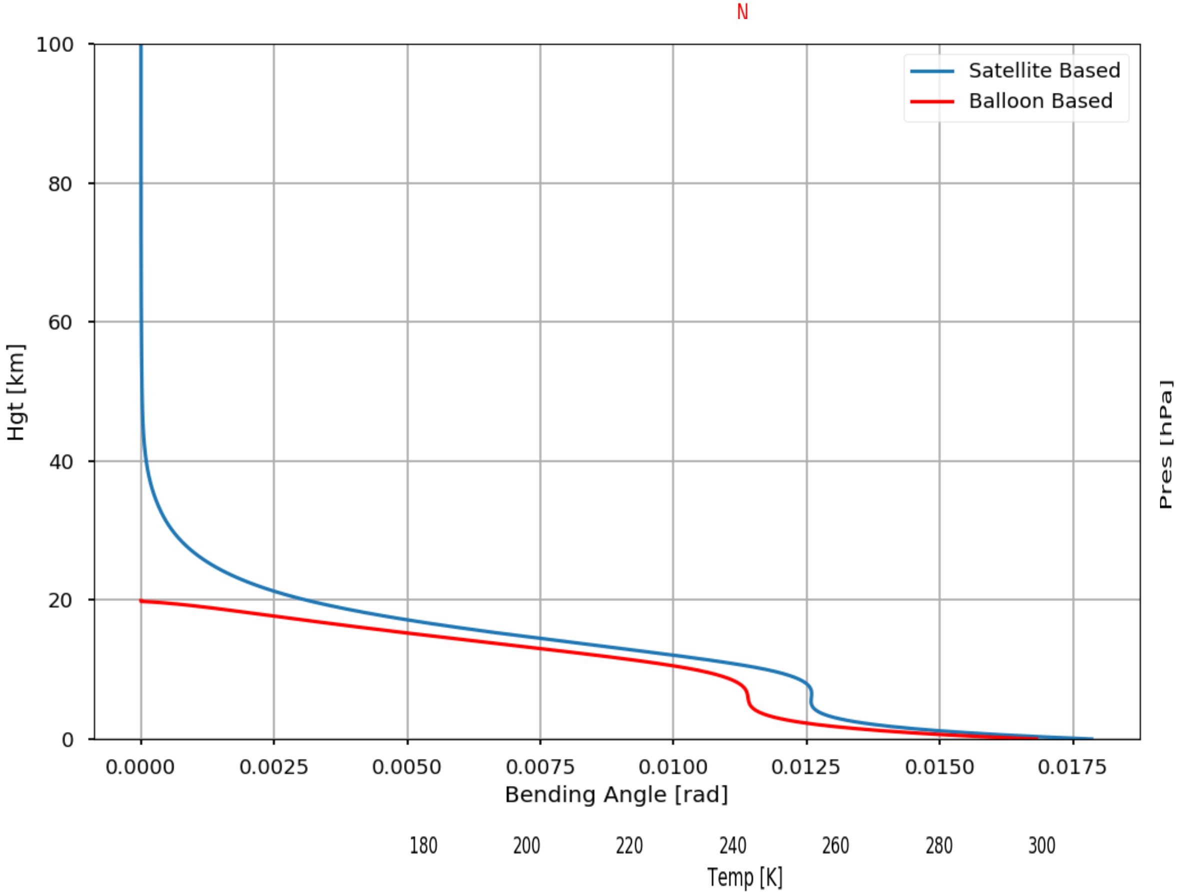
Integration to infinity:
LEO-based Bending Angle

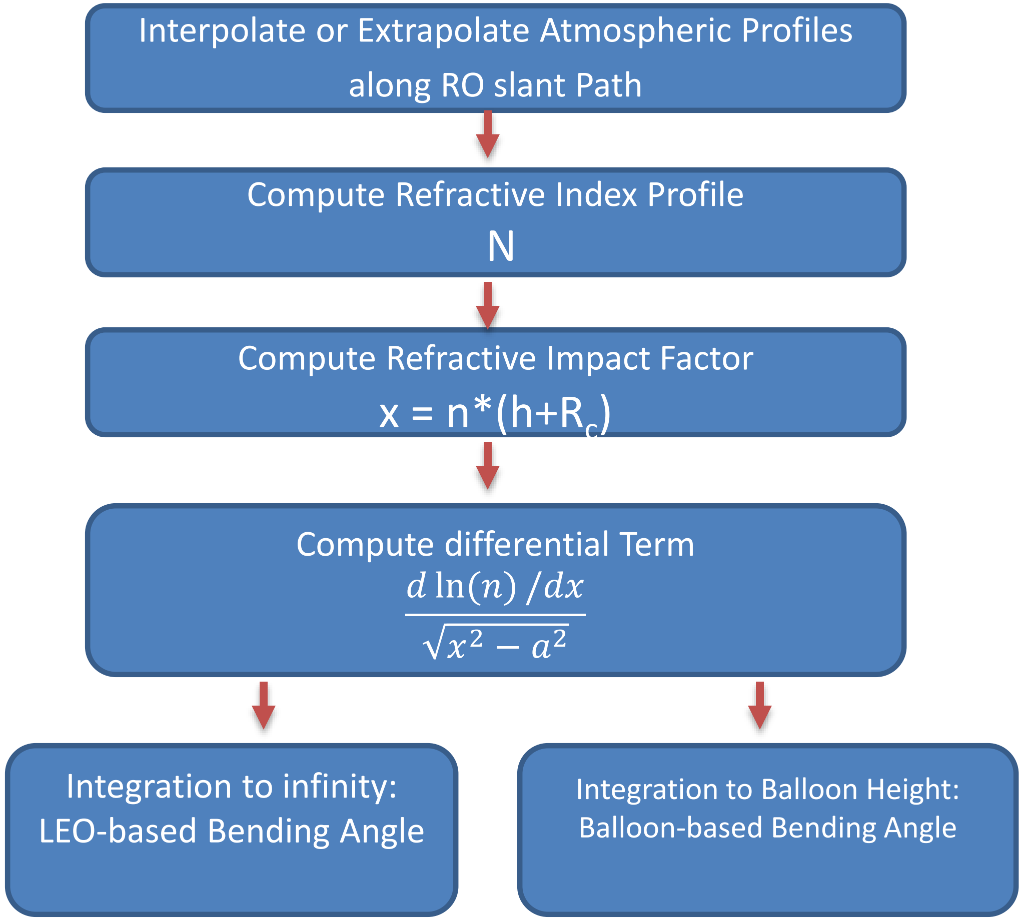
$$\alpha(a) = -2a \int_a^{\infty} \frac{\frac{d\ln n}{dx}}{(x^2-a^2)^{1/2}} dx$$

Integration to Balloon Height:
Balloon-based Bending Angle

$$\alpha'(a) = -2a \int_a^{n^{R} r^{R}} \frac{\frac{d\ln n}{dx}}{(x^2-a^2)^{1/2}} dx$$

GPS RO Bending Angle Forward Operator (ii)





Interpolate or Extrapolate Atmospheric Profiles along RO slant Path

Compute Refractive Index Profile

N

Compute Refractive Impact Factor

$x = n*(h+R_c)$

Compute differential Term

$$\frac{d\ln(n)/dx}{\sqrt{x^2-a^2}}$$

Integration to infinity: LEO-based Bending Angle

Integration to Balloon Height: Balloon-based Bending Angle

$$\alpha(a) = -2a\int_a^{\infty}\frac{\frac{d\ln n}{dx}}{(x^2-a^2)^{1/2}}dx$$

$$\alpha'(a) = -2a\int_a^{n^R r^R}\frac{\frac{d\ln n}{dx}}{(x^2-a^2)^{1/2}}dx$$

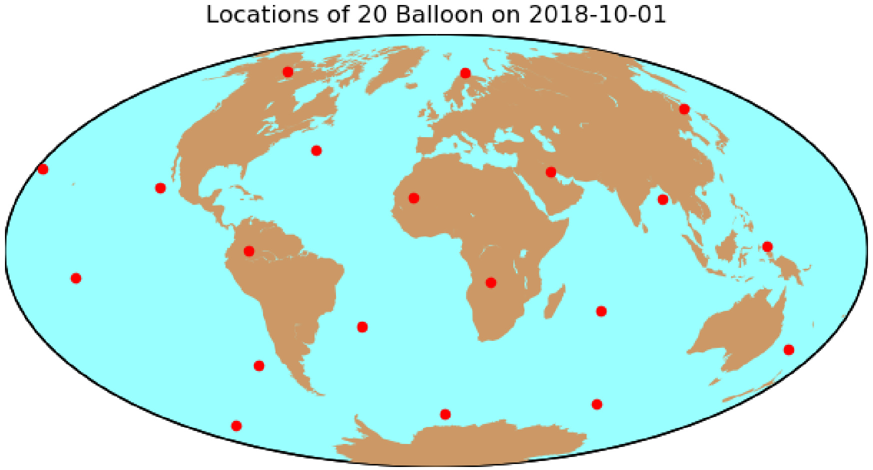
Building the constellation for OSSE

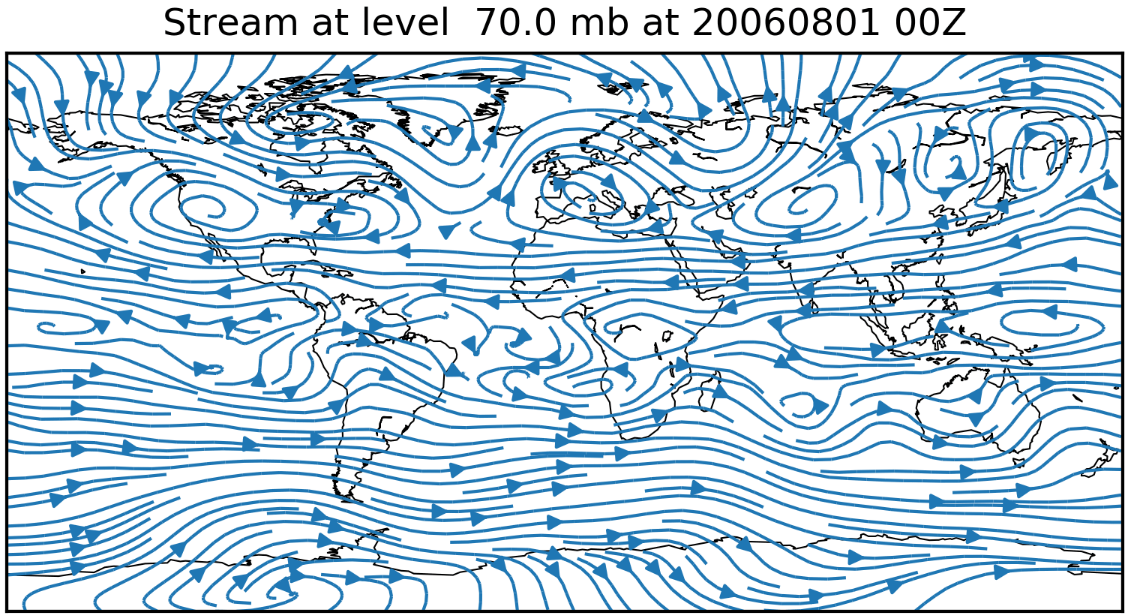
20 balloons provide observation count similar to satellite (using current GPS transmitters)

Seed the balloons for global coverage, and use trajectory model to transport according to G5NR flight level wind fields

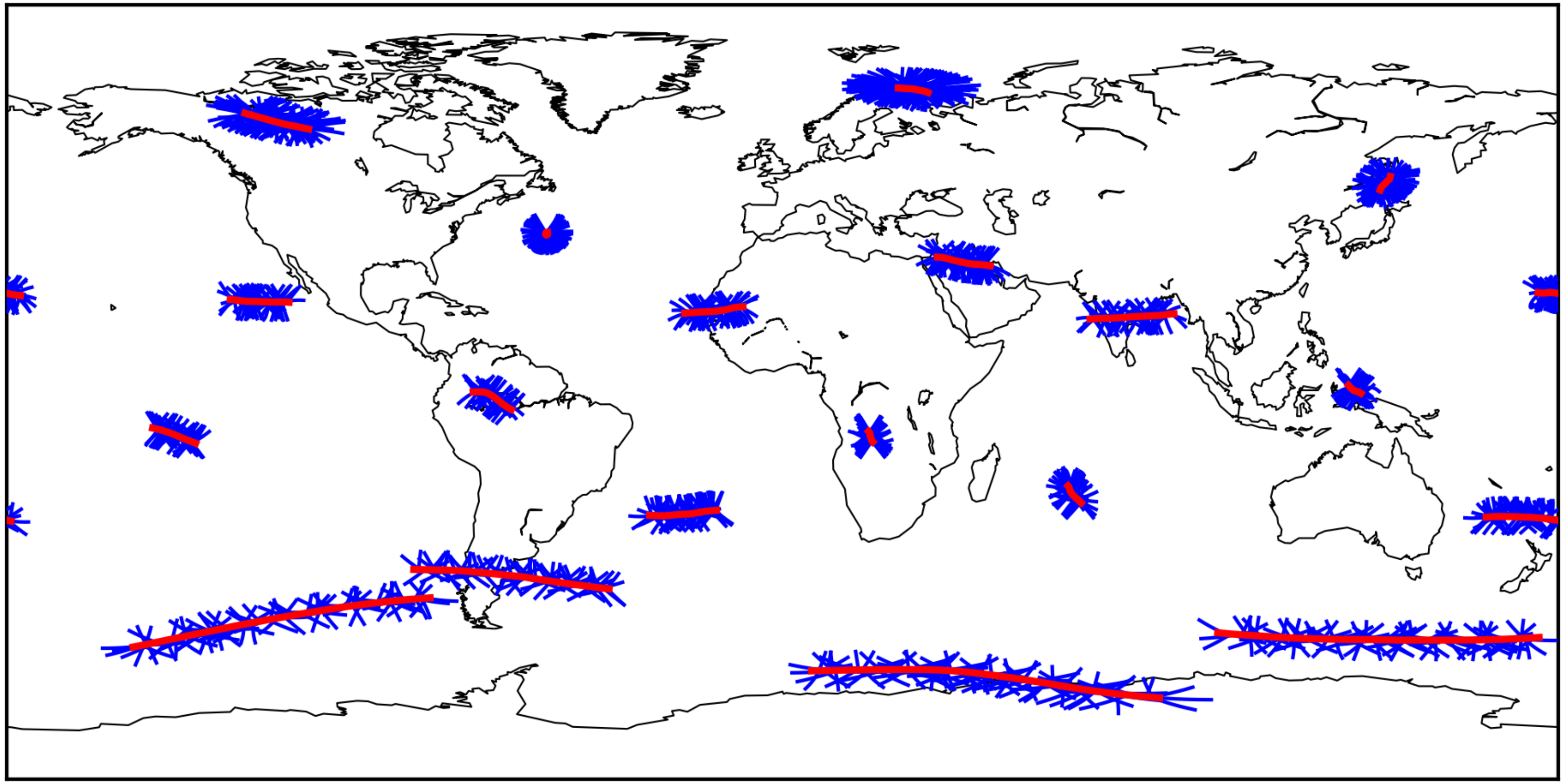
Simulate balloon GPSRO bending angle

No added complexity (for maneuvering)



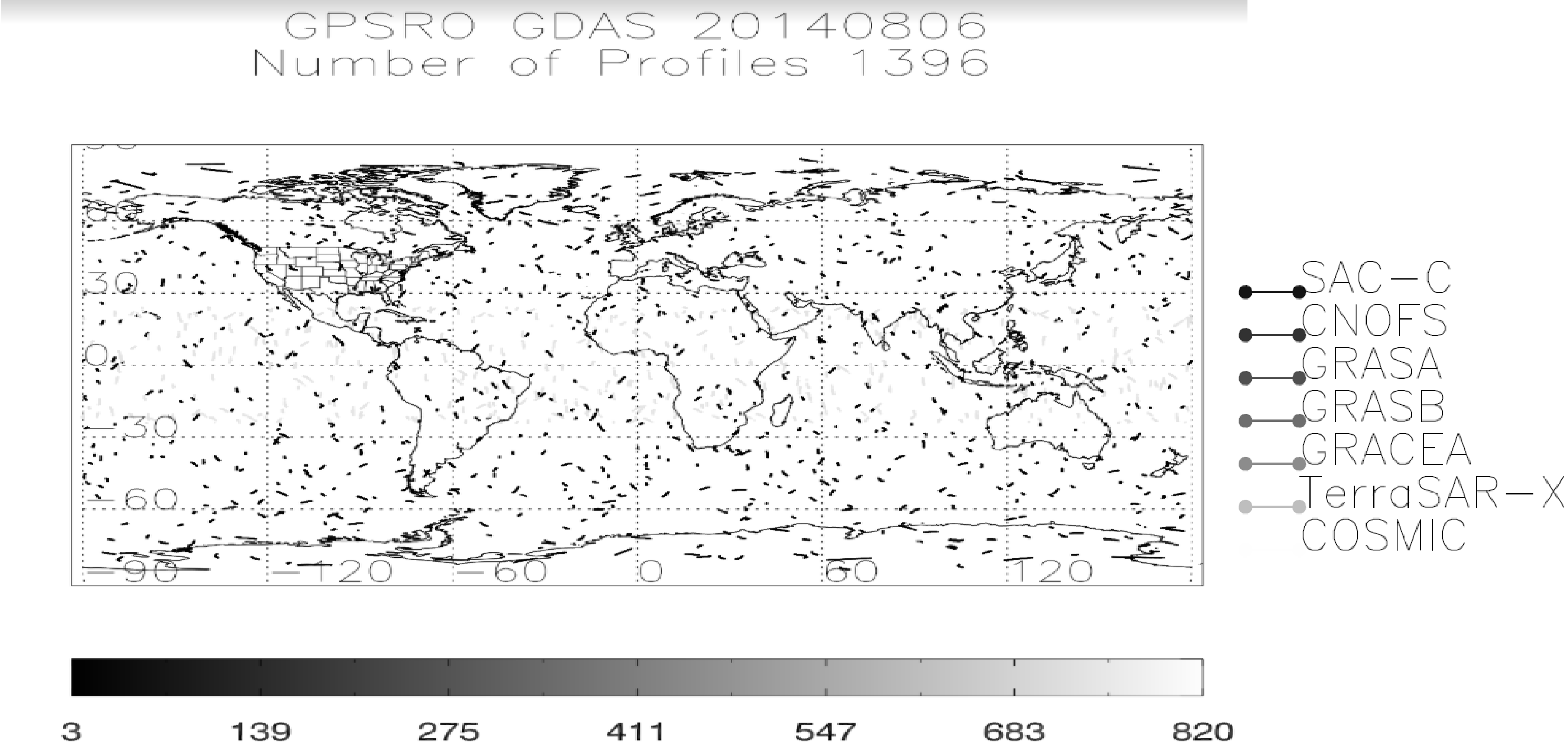


Distribution of balloon-based RO for One day with 20 Balloon Trajectories



20 Balloons, 1719 GPS RO profiles

One Day’s Satellite GPS RO from GDAS



The number of Balloon RO profiles from balloon should be approximately comparable to satellite GPS RO to fairly evaluate the impact of assimilating balloon GPS ROs.

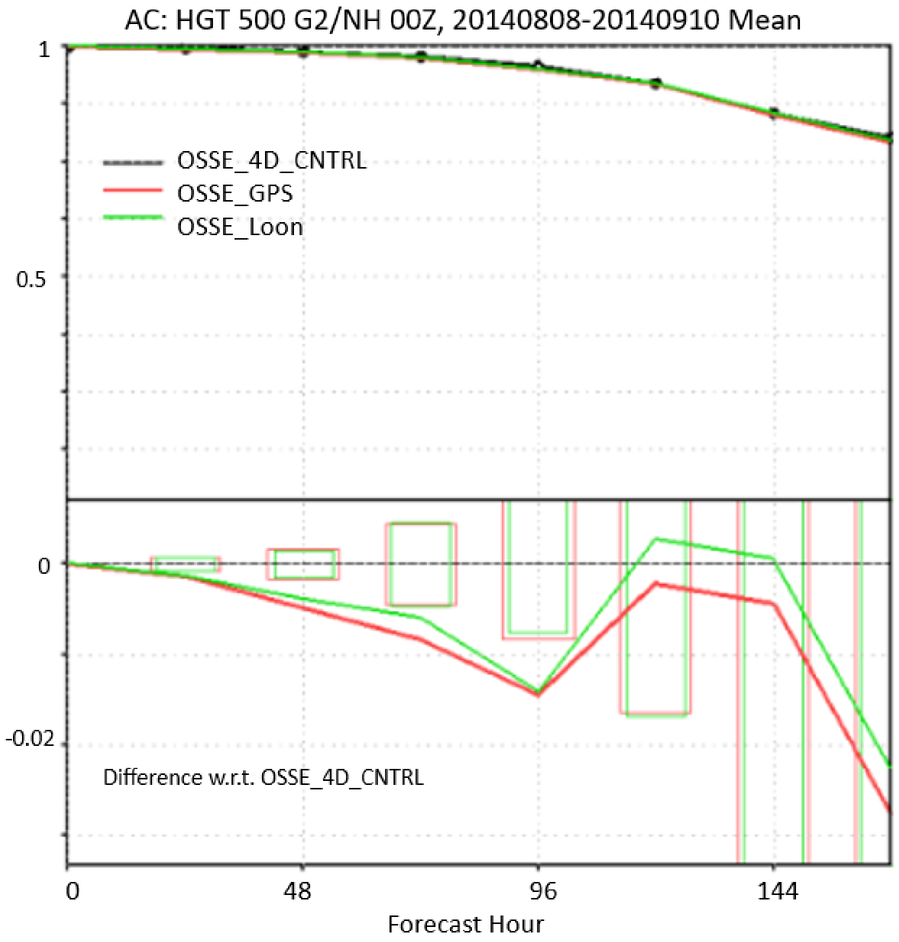
OSSE setup

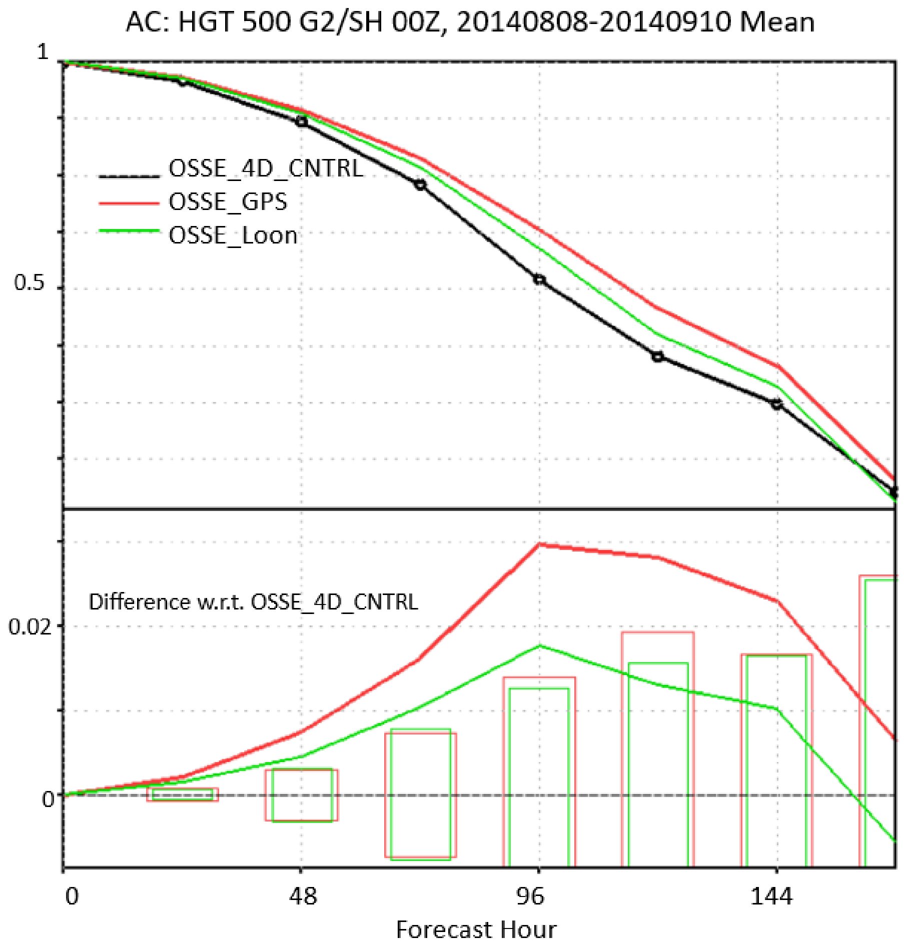
- Utilize the CGOP, with G5NR August-September (2006)
  - Uses 4DEnsVar, GFS is GSM
- Integrate balloon GPSRO as RO subtype using same forward operator, obs error and QC
  - QC required slight modification o delta-X threshold

Current OSSE Configuration

	OSSE_4D_CNTRL	**OSSE_GPS**	**OSSE_Loon**
Conventional Data	Assimilated	Assimilated	Assimilated
Satellite GPS RO		Assimilated	
Loon GPS RO			Assimilated

Balloon-based OSSE results, 500 hPa Height Anomaly Correlation


AC: HGT 500 G2/NH 00Z, 20140808-20140910 Mean


AC: HGT 500 G2/SH 00Z, 20140808-20140910 Mean

Overall, the RMS score reduced when satellite or Loon GPS were assimilated, and anomaly correlation score increased while satellite or Loon were assimilated, which indicates positive tendency of the impact.

Content

- Loon internet platform
  - Flight dynamics, measurements, hosting capability
  - Loon validation capability
  - Loon potentially-hosted instrument simulations
    - Passive MW Sounder or GPS RO instrument
  - OSSE experiment evaluations (GPS ROs)

- **Extending space internet platform**
  - **Space-X Starlink Platform**

- Summary

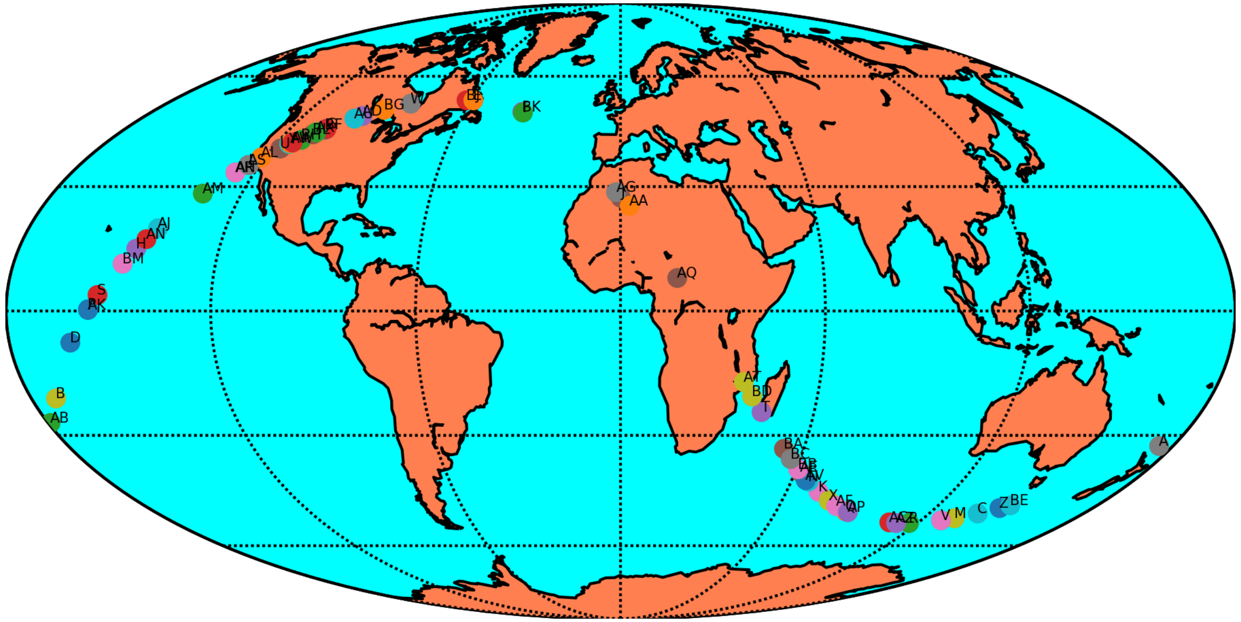
Space-X StarLink Constellation

- **Starlink** is a satellite constellation development project underway by SpaceX, to develop a low-cost, high-performance satellite bus and requisite customer ground transceivers to implement a new space-based Internet communication system

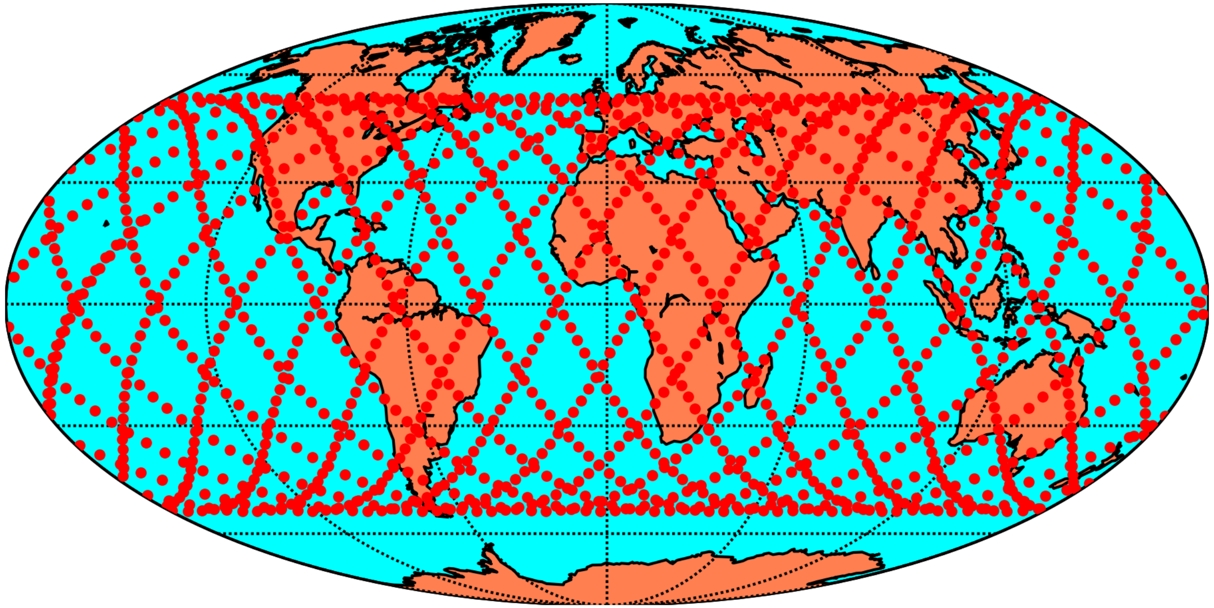
Phase	No. of Orbit planes	Satellites Per Plane	Total satellites	Orbit Altitude (km)	Orbit Inclination angle (Degree)
1	**24**	**66**	**1584**	**550**	**53**
2	32	50	1600	1100	53.8
3	6	75	450	1325	70
3	8	50	400	1130	74
3	5	75	375	1275	81

- SpaceX also plans to sell satellites that use a satellite bus that may be used for military, scientific or exploratory purposes.

Launch on 24 May 2019


2019-06-09T00:00:00

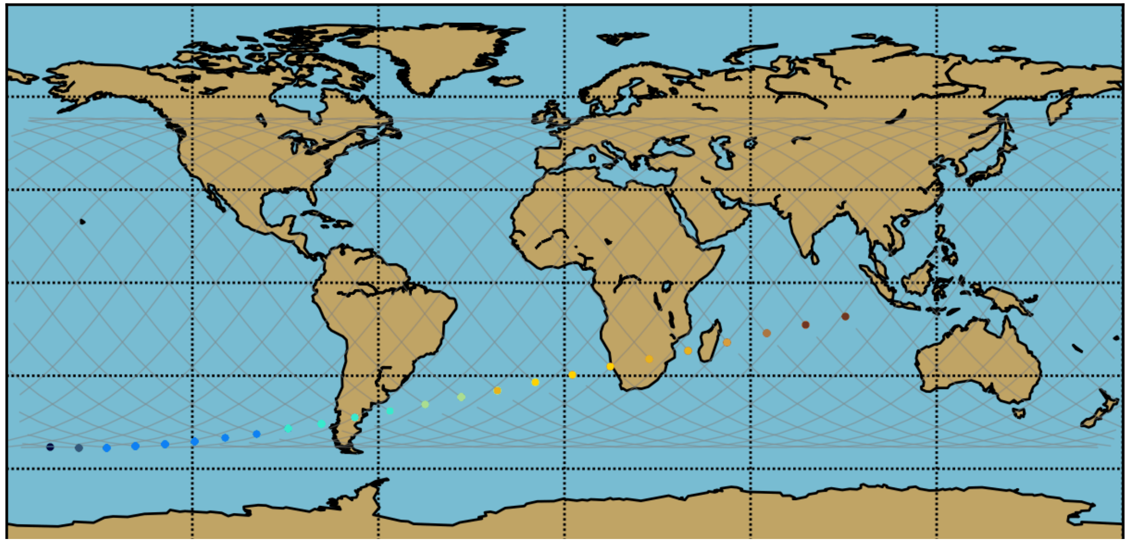
The 60 operational satellites were launched on 24 May 2019


One satellite orbit track

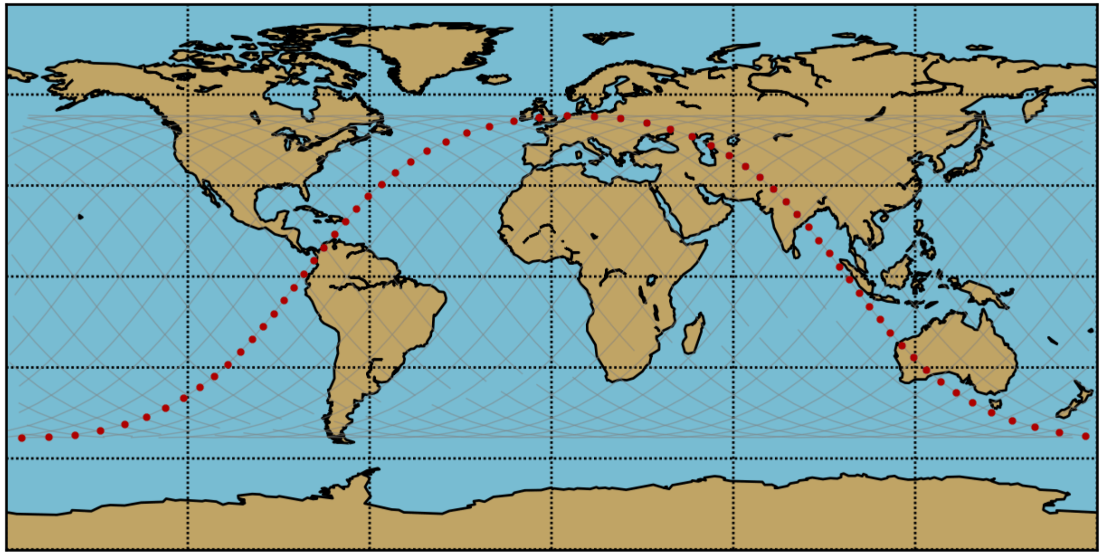
STARLINK A

Orbit altitude: 436-454 km Inclination: 53.5 Degree
Orbit period: 93.3415736139 minutes

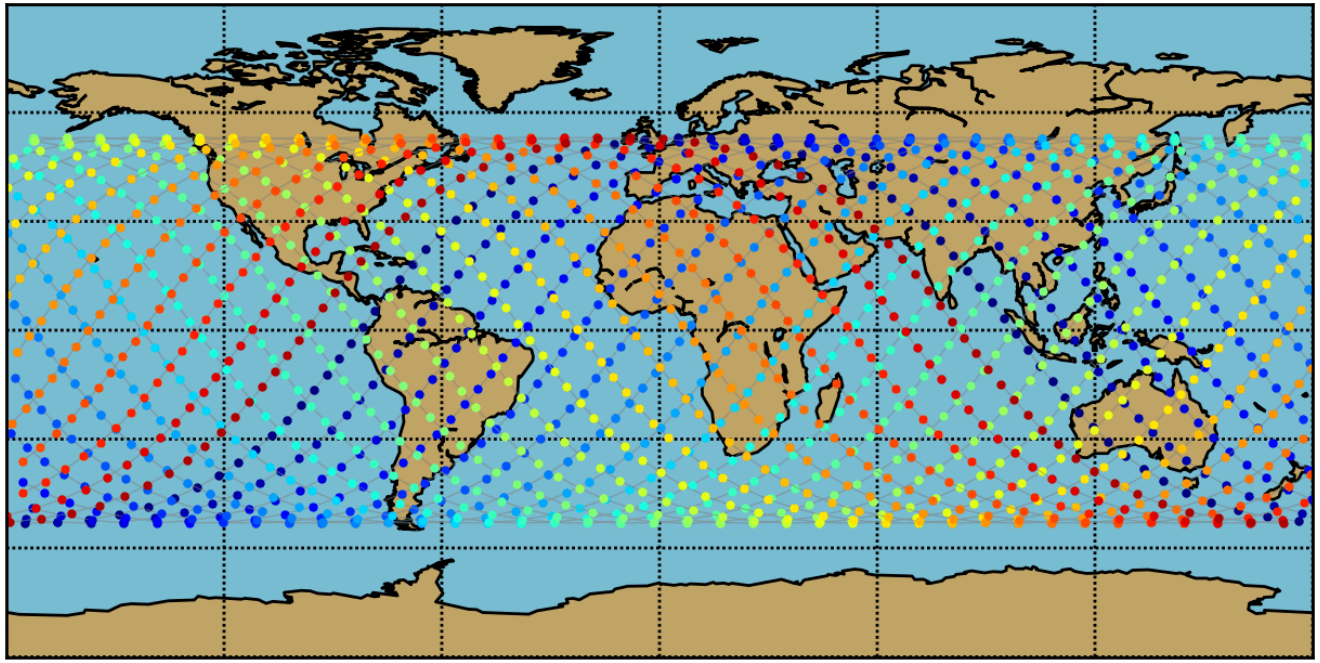
Phase 1 Simulations : 1584 Satellites


2019-05-27T00:00:00

24 orbit planes and each orbit plane shifts 15 degree.

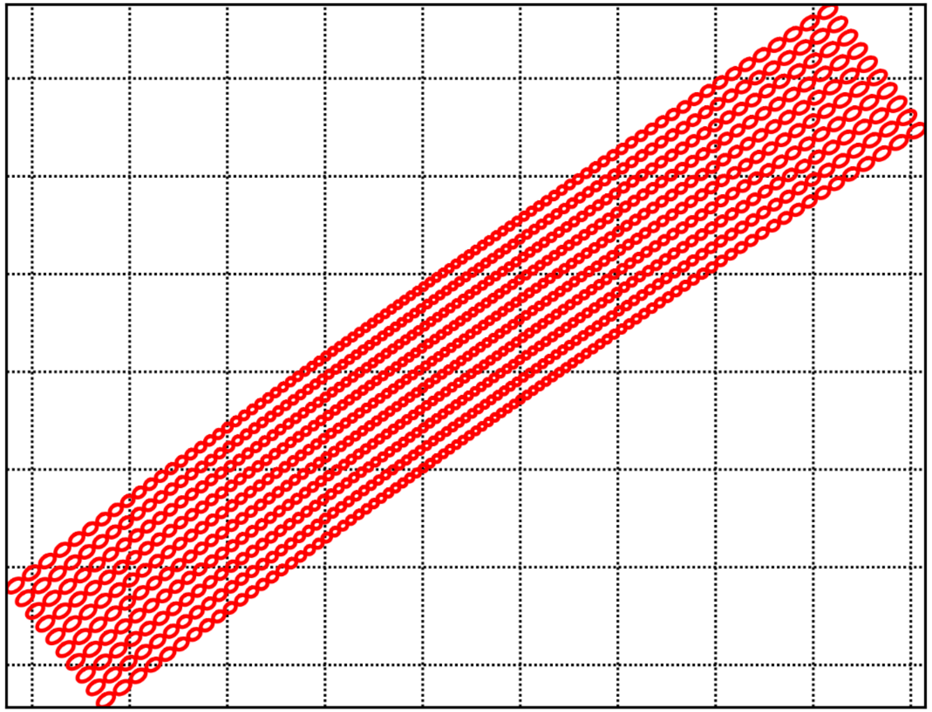

2019-05-27T00:00:00

Each orbit plane contains 66 satellites. Every 1.5 minutes, have satellite

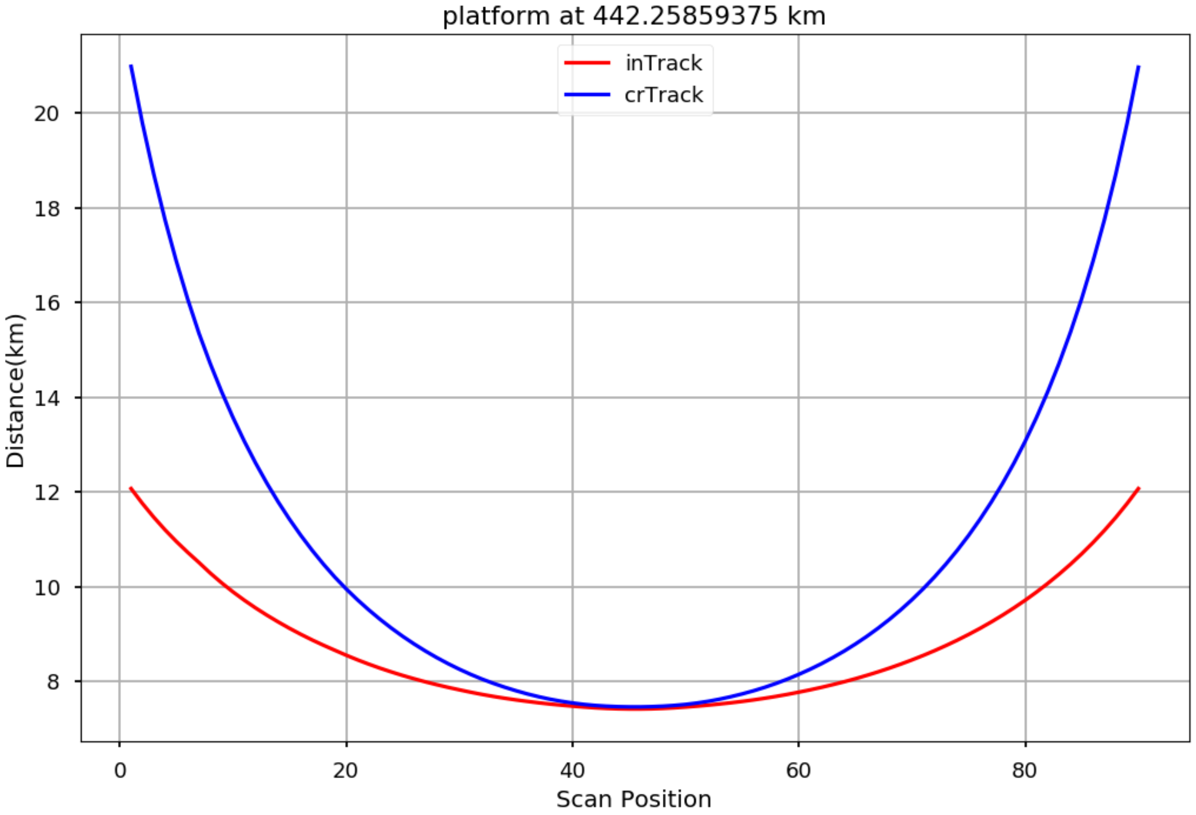

2019-05-27T00:00:00

To avoid crushing, each satellite has phase shift:
360°/24/ 66
Using the launch satellite orbit parameter: 53 °
Inclination angle with ~ 440 km orbit altitude

Adding Scan on StarLink Satellite

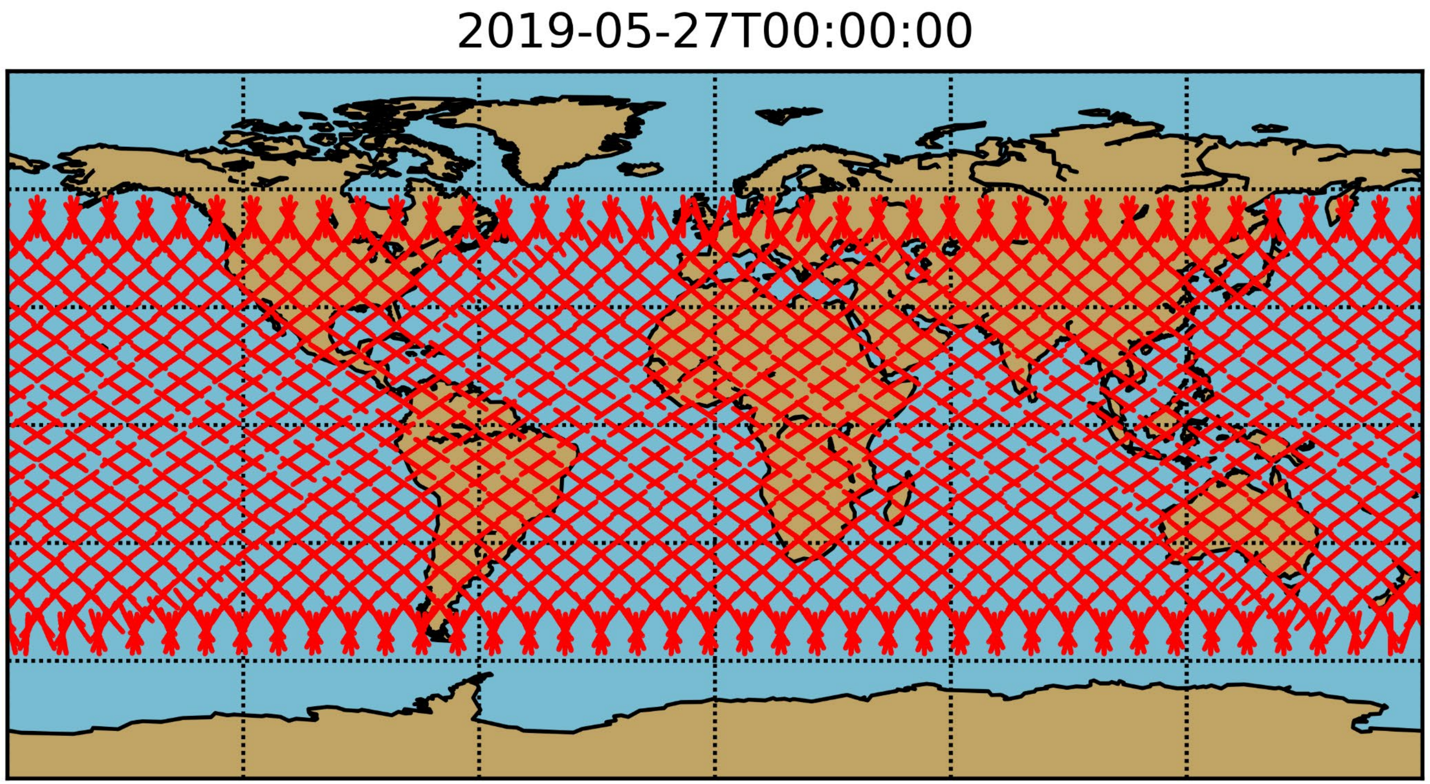


step_angle = 1.1 Degree
90 FOVs in Every Scan
max_scan_angle = 49.5 Degree
fov_angle = 0.963 Degree
Scan Rate: 8/3 seconds per Scan



Cross-track and in-Track FOV footprint size on Ground

One Scan (in 2.7 seconds) from all satellites

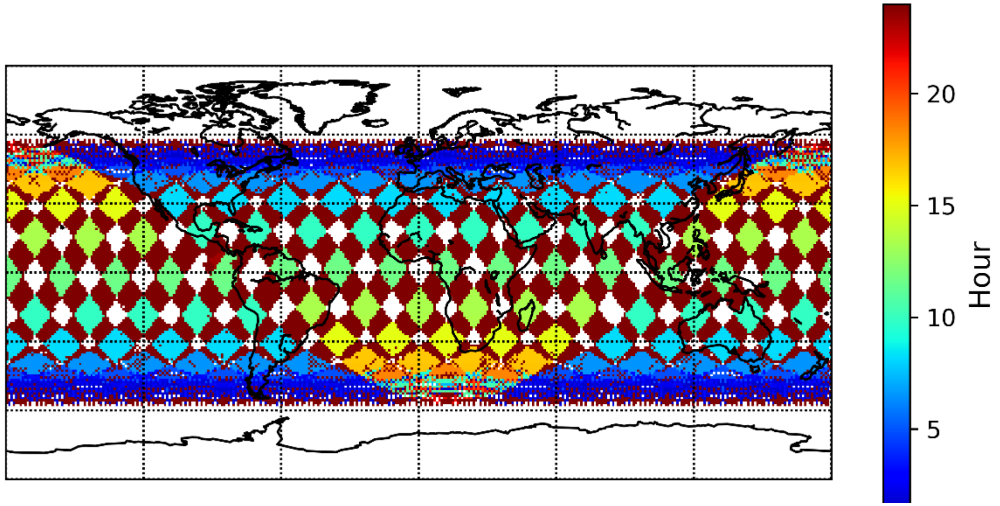


- Question :

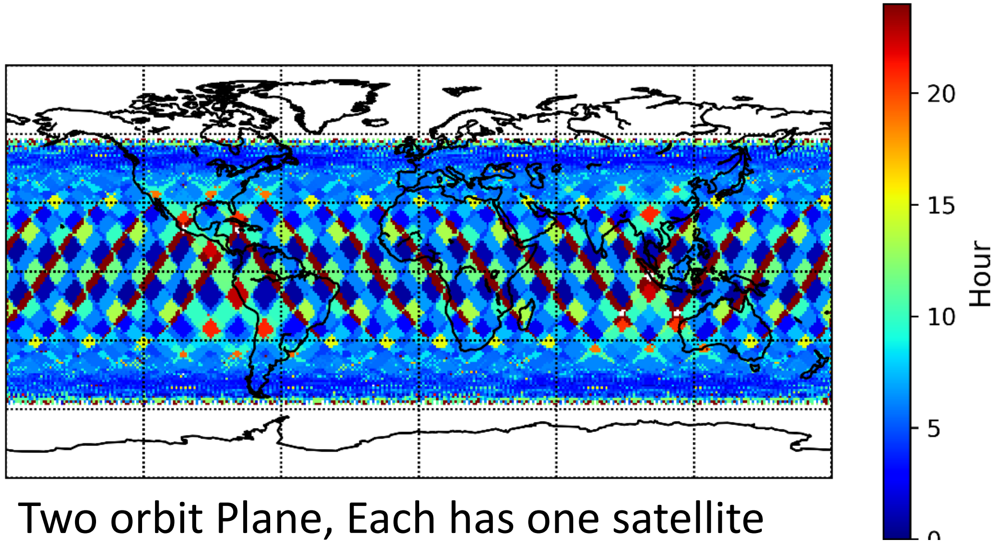
  How many satellites do we need in order to get global images (observations) every 15 minutes (like GOES) using StarLink consternation?

- Method:
  - Simulate 24-hours’ data with Scan Mechanism
  - Count how many observations in each grid box (mean refresh rate)
  - Orbit plane goes first, and then add satellite in each orbit plane

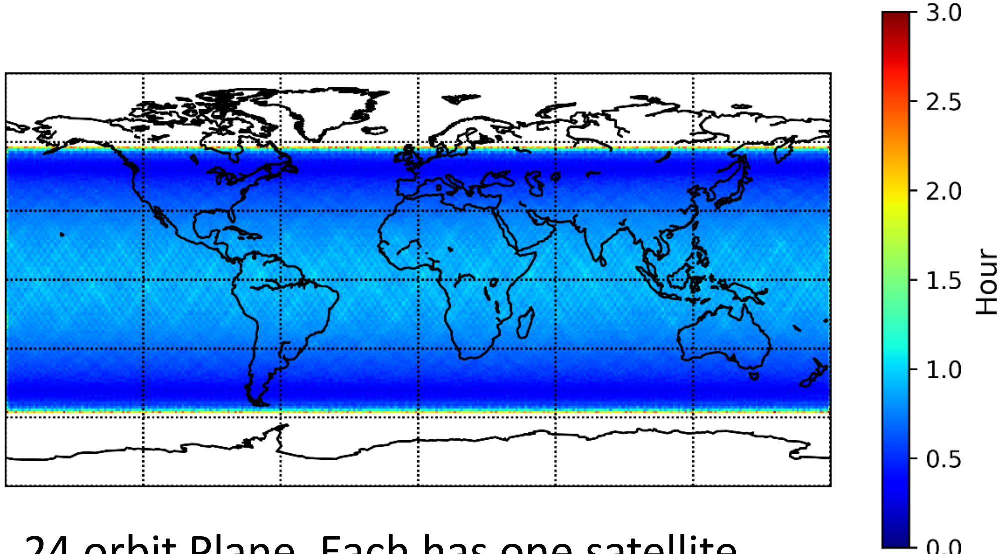
Local Refresh Rate



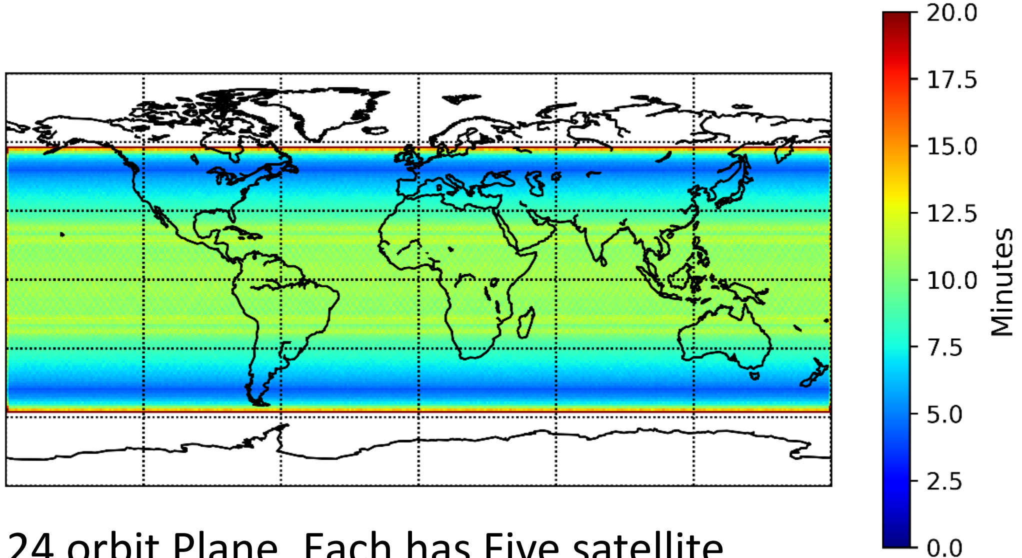
One orbit Plane, Each has one satellite



Two orbit Plane, Each has one satellite

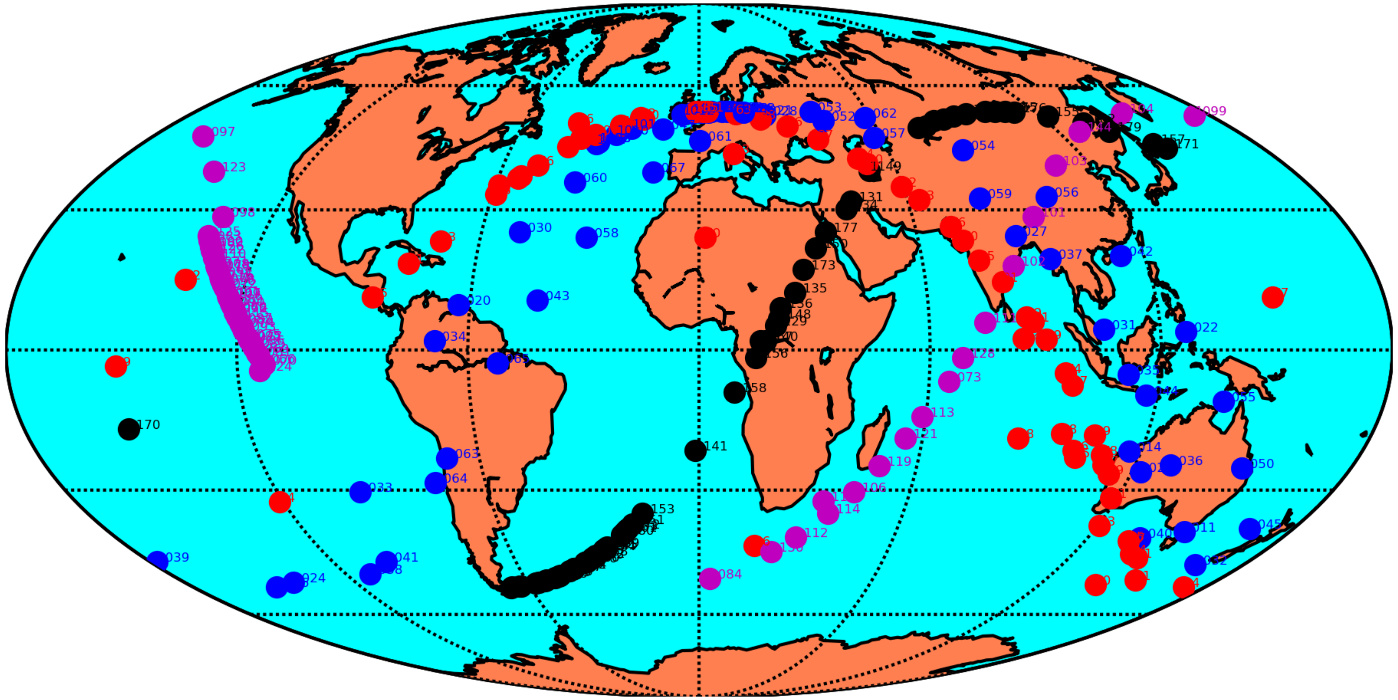


24 orbit Plane, Each has one satellite



24 orbit Plane, Each has Five satellite

StarLink Current Status


2020-02-14T00:00:00

StarLink0: Launched on 05/29/2019

StarLink1: Launched on 11/11/2019

StarLink2: Launched on 01/07/2020

StarLink3: Launched on 01/29/2020

Concluding Remarks

- Emerging internet platforms provide future opportunities for future satellite sensor hosting opportunities
- Loon-based GPSRO constellations have been simulated and assessed within NOAA GFS via OSSE
- StarLink constellation platform provide geostationary-like observations with appropriate configuration
- Many tools have been developed in STAR to simulate space and near-space constellations and hooked to existing sensor simulation capabilities (CGOP)