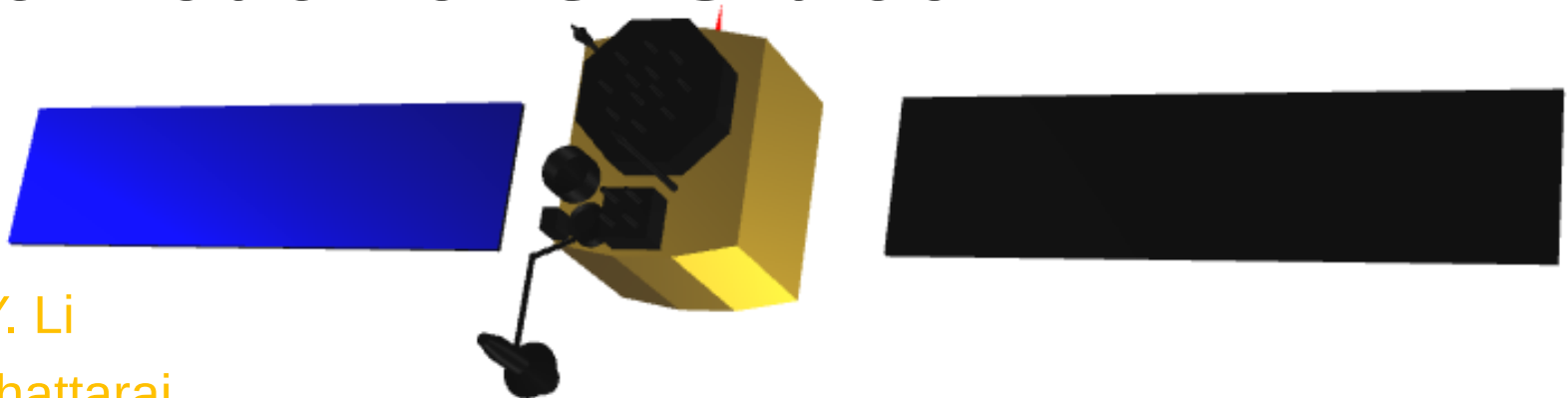


Developing a high precision physics-based analytical radiation force model for GPS block IIF

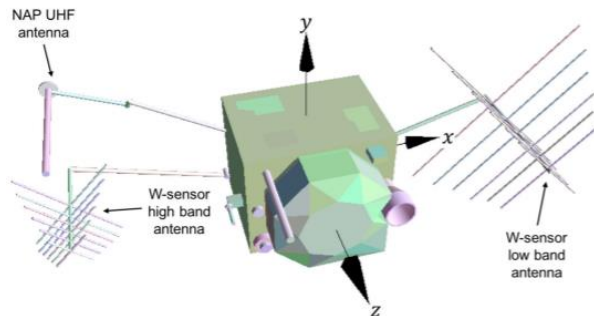


Grace R. Y. Li

Santosh Bhattarai

GPS

- GPSIIF manufactured by: 
- Operated by: US Air Force
- Orbit period: 12 sidereal hours
- Biggest limitation: lack of access to information on GPS block IIF satellites.

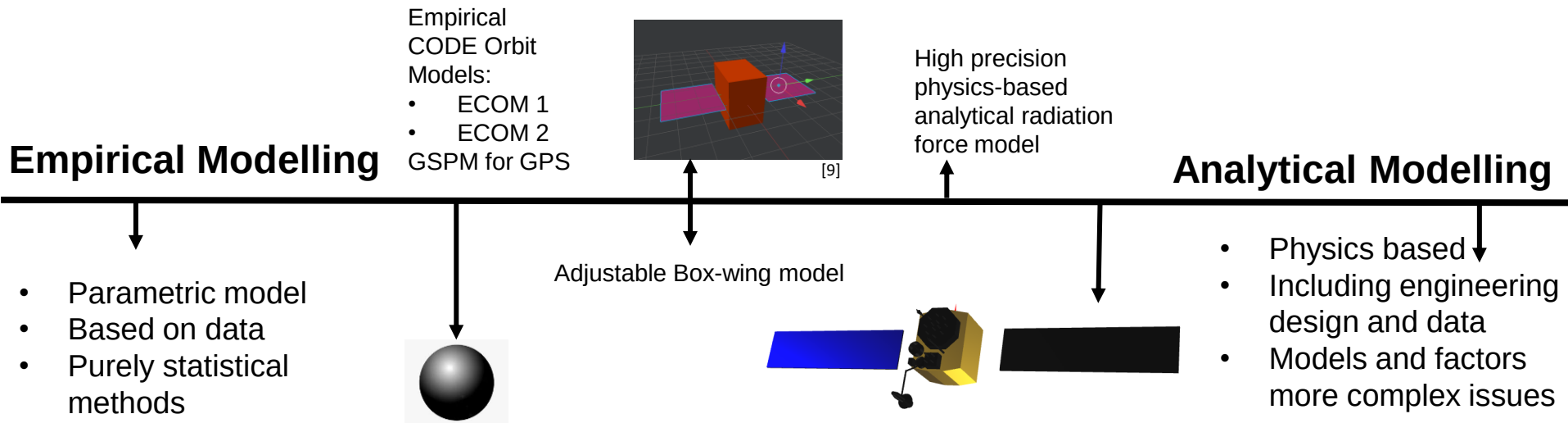


GPS block IIR

- UCL has conducted previous work on GPS by modelling the GPS block IIR.
- The model achieved sub-metre level errors in 12-hr orbit prediction tests used internally for model verification. [1]
- The figure shows the GPS block IIR model which is also seen in the figures describing the pixel array computation schemes in slides:

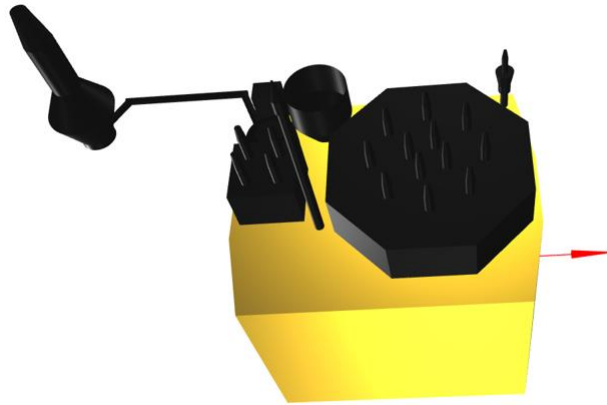
Radiation force modelling methods

- Current modelling methods can be classified on a spectrum that ranges from empirical to analytical modelling with the ultimate goal of achieving more precise and accurate orbits.
- UCL's high-fidelity analytical radiation force (HARF) modelling of satellites are physics-based models that can incorporate much more complex factors such as shadowing and secondary reflections.



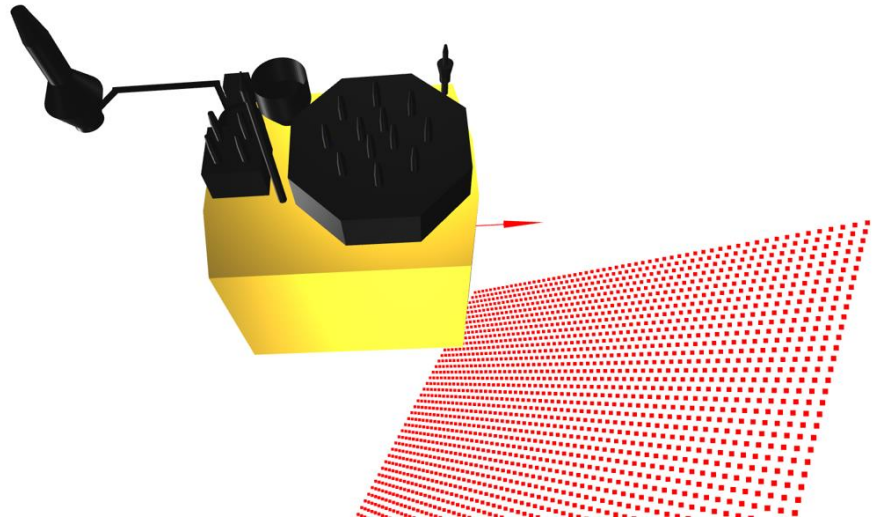
Analytical Solar Radiation Pressure and Thermal Re- radiation Modelling Software

UCL's SGNL group have developed software to compute the radiation force model of satellites from an accurate spacecraft model (similar to the figure shown below.)



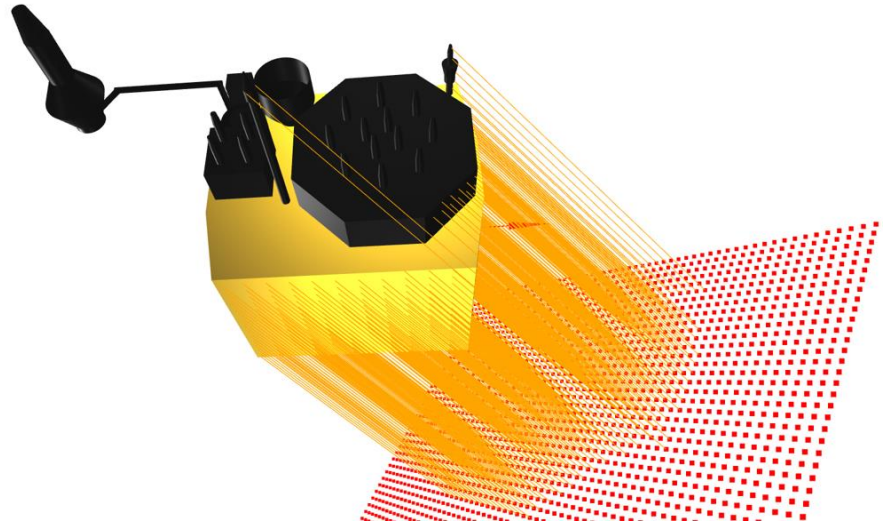
Analytical Solar Radiation Pressure and Thermal Re- radiation Modelling Software

The software uses pixel arrays to simulate the radiation source (the Sun) at a given longitude and latitude and distance around the spacecraft model.



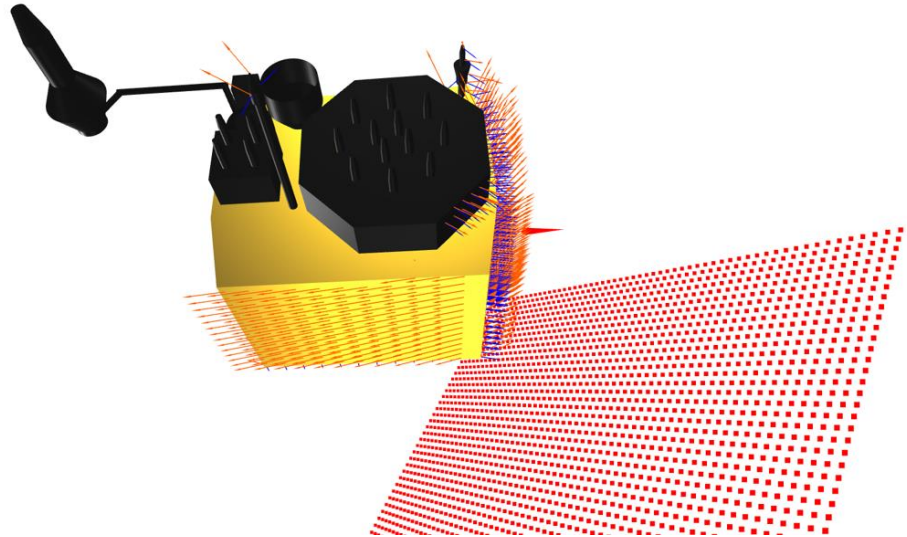
Analytical Solar Radiation Pressure and Thermal Re- radiation Modelling Software

Rays are then produced from the pixel array points and are projected onto the spacecraft model.



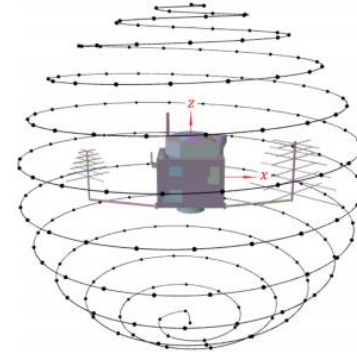
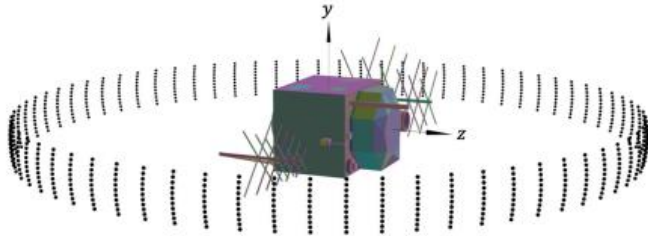
Analytical Solar Radiation Pressure and Thermal Re- radiation Modelling Software

The intersecting points of the rays on the surface of the spacecraft generate normal and reflections from the spacecraft information given at each intersection point and the acceleration due to the interaction of forces at these points



Process: Pixel array computation schemes

To produce the radiation force model the pixel array method two computation schemes are used to generate radiation sources in every direction around the spacecraft. [1]



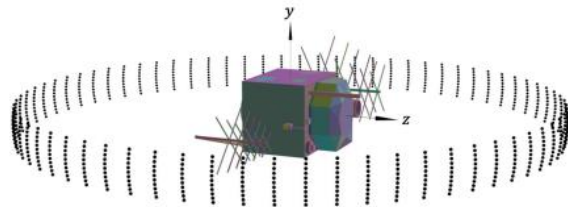
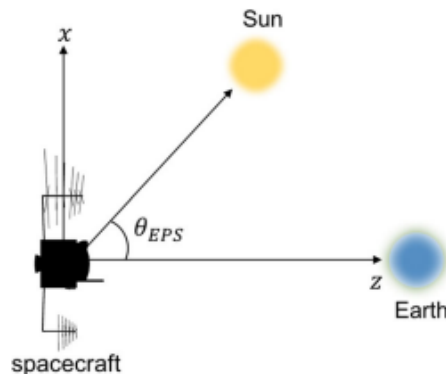
Process: Pixel array computation schemes



EPS (Earth-Probe-Sun) sweep scheme

Attitude Control Laws: By design antennas(+Z axis) points to Earth.

- Solar panels move in the Y-axis to optimise solar radiation.
- Spacecraft is confined to the Body-fixed system X-Z plane.
- Pixel array of 360 points (EPS=1 deg) are uniformly distributed about spacecraft in X-Z plane.
- In the Y-axis, points are rotated by 1 degree for 10 degree arcs.
- This scheme has incomplete coverage of s/c in all directions. [1]

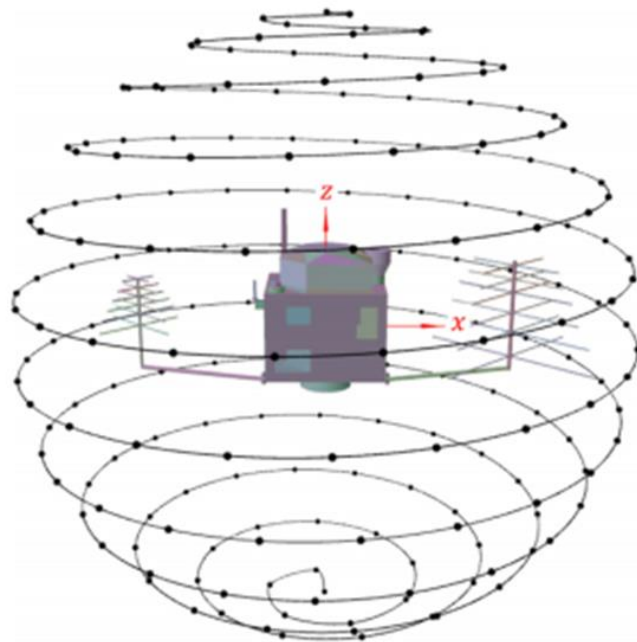


Process: Pixel array computation schemes



Spiral Points Scheme

- To compensate incomplete coverage of EPS sweep scheme, spiral points scheme is used.
- 10,000 points spaced out equally along the spiral path from the north to south pole. [1]



Project Structure

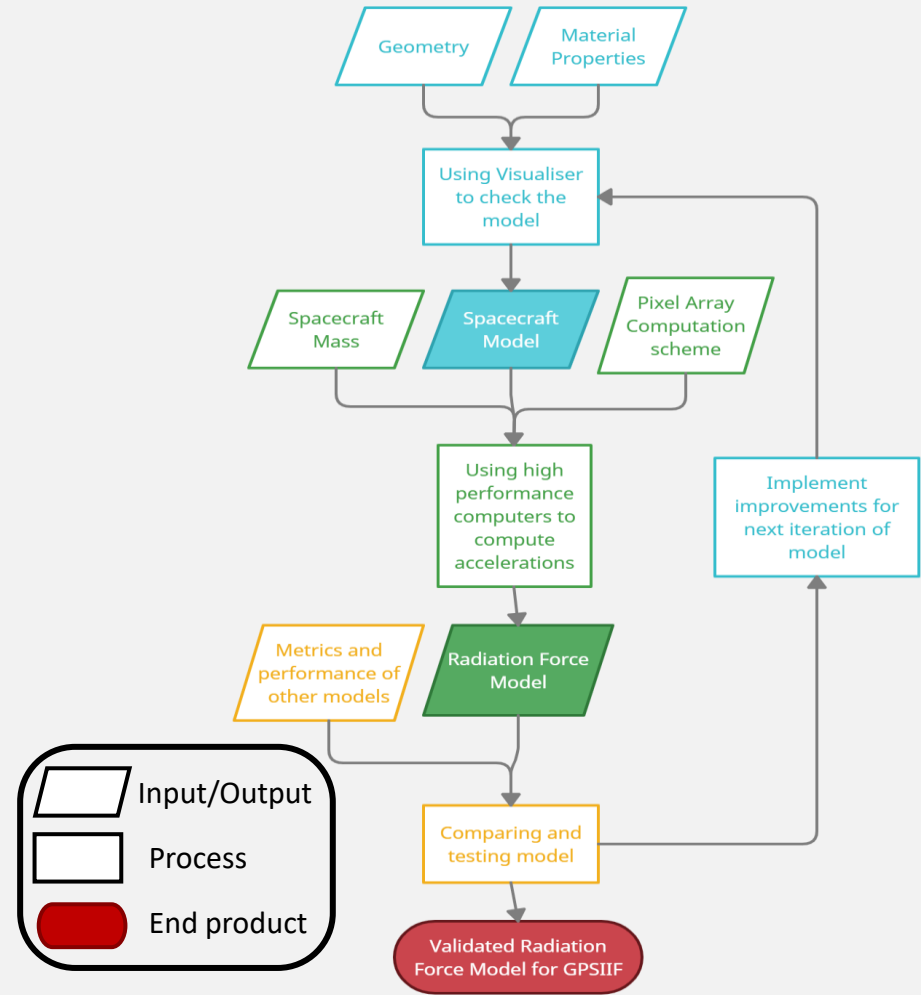
- The flowchart shows the general project structure, splitting the project into 3 components:

Component 1 • Spacecraft Model

Component 2 • Radiation force model

Component 3 • Validation of the model

- Focus will be placed onto components 1 and 2 due to time limitations and components 1 and 2 for iterations of the model will be run in parallel.



Component 1: Producing the spacecraft model



Input: Design and technical specifications of GPSIIF



Process: General checks on the visualiser and suggestions for improvements for the next iteration of the model



Output: Spacecraft model

Component 1: Spacecraft model

Input: Data Sources

Using following sources to provide information on the GPS block IIF satellite to build s/c model:

- Available images
- Literature
- Potentially – scale model of GPSIIF in the Science Museum, London
- Expert's opinions (Engineers, manufacturers) for justifications or suggestions.
- The Sheldahl Redbook

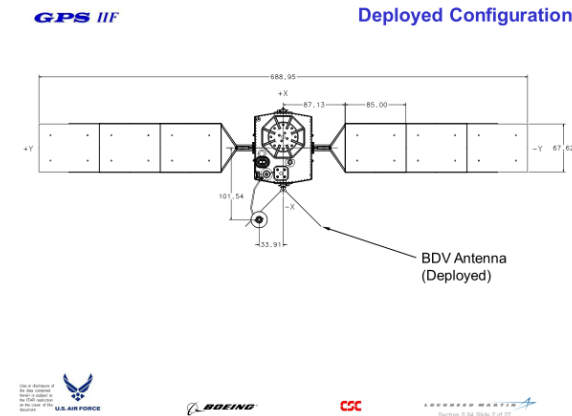
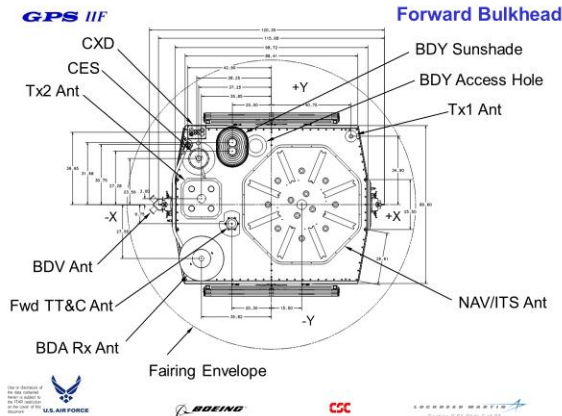
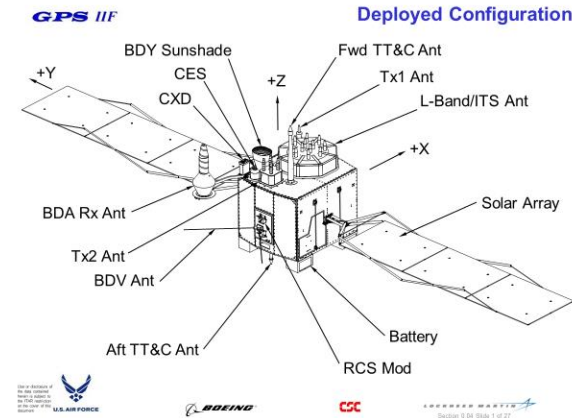
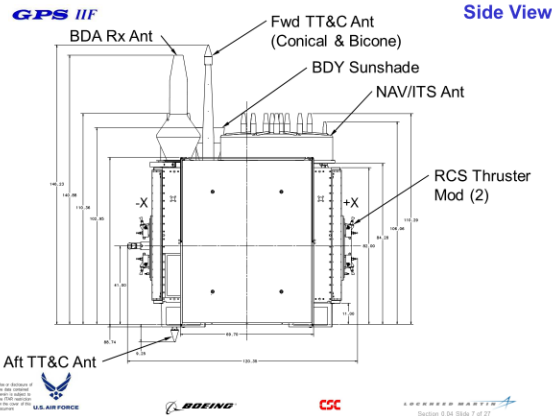


Image shows the 1:1 scale model of GPSIIF in The Science Museum, London [3]

Component 1: Spacecraft model

Input: Geometric Model

- Based off technical drawings [2] – not complete in terms of all measurements
- Geometric model of instruments on the main bus that required more detail in terms of the individual components used ratios to overall drawings as drawings are to scale.



Component 1: Spacecraft model

Process: Building basic geometric model from individual components

- Software uses ASCII text file format for s/c components.
- S/C description file is broken down into:
 - Line 1: type of component
 - Line 2: comment line
 - Line 3: dependent on component type (number of vertices)
- Following X, Y, Z points of components in m
- Final line: Material properties

```

GENERAL
0 // 001 0001 +Z_face:MLI
8
-1.122934 1.023620 1.041400
-1.253744 0.323850 1.041400
-1.253744 -0.323850 1.041400
-1.122934 -1.023620 1.041400
1.122934 -1.023620 1.041400
1.253744 -0.323850 1.041400
1.253744 0.323850 1.041400
1.122934 1.023620 1.041400
0.650000 0.500000 0.830000 0.020000

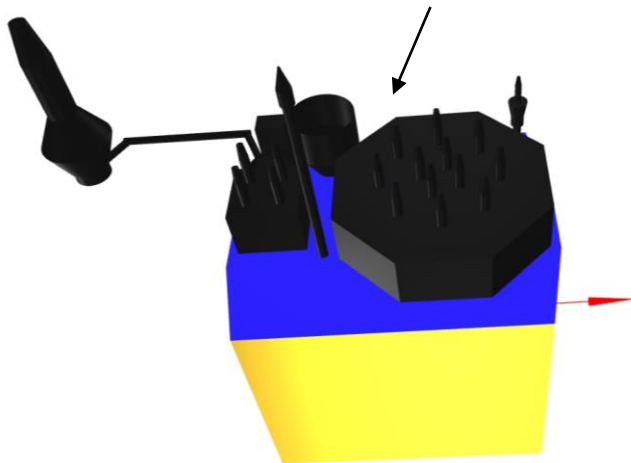
```

```

Component Name
0 001 0001 +Z_face:MLI
Specularity
0.500000
Reflectivity
0.650000
Emissivity
0
Emissivity_effective
0
Material
001
Area(m^2)
4.9504
Camera Position
0.458,-4.327,5.329
Camera Direction
-0.067,0.629,-0.775

```

Component 0 shown in the ASCII text file translates to the polygon highlighted in blue in the figure of the model.

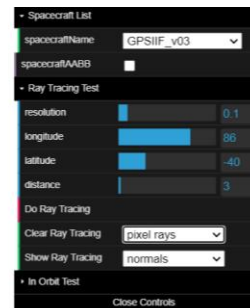
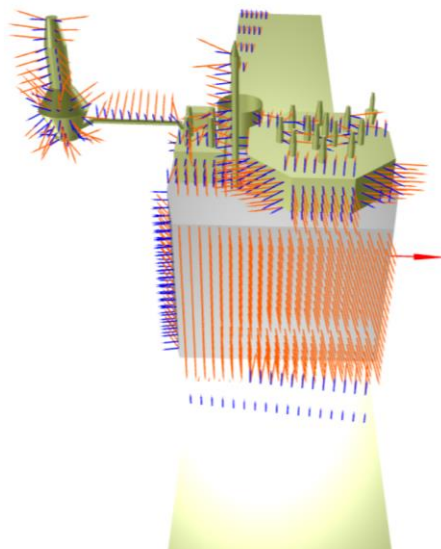


Component 1: Spacecraft model

Process: Quality Control

Using the visualiser tool, ray tracing tests were conducted periodically for sanity checks of the spacecraft model.

rate, "p" to screenshot



Component 1: Spacecraft model

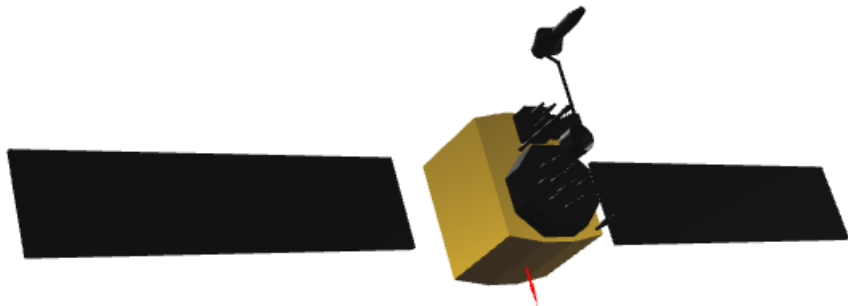
Output: GPSIIF_v02

- Building initial geometric model resulted in version 2 of GPSIIF – a basic box-wing style model.



Output: GPSIIF_v03

- Building instruments on the bus of the geometric model resulted in version 3 of GPSIIF - which serves as the basic geometric model to use for testing material properties in following iterations.



Component 1: Spacecraft model

Input: Material Characteristics

The spacecraft model requires a material type and 4 material characteristics for each component:

- Reflectivity
- Specularity
- Emissivity
- Effective emissivity

From GPSIIF_v04 and onwards, we will focus on material properties of the model.



[4]

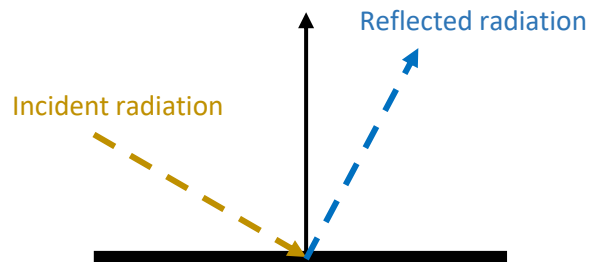


[5]

Component 1: Spacecraft model

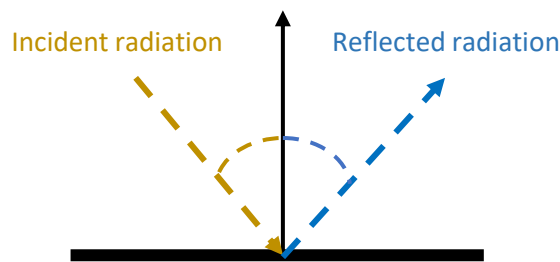
Reflectivity

The reflectivity of a material is the proportion of incident radiation that is reflected from the surface. It is a value between 0-1.



Specularity

The specularity of a material is the proportion of reflected radiation that is reflected in a mirror-like (specular) manner. It is a value between 0-1.



Emissivity

The emissivity of a material is a measure of how efficiently the material is able to radiate energy.

Effective Emissivity

Effective emissivity is the proportion of absorbed energy that is transmitted through the spacecraft.

Component 1: Spacecraft model

Process: Testing material property values

- Develop a method for testing the property values used for spacecraft model.
- Currently using Sheldahl Redbook range values as upper and lower limits for material properties and varying values in equal increments.

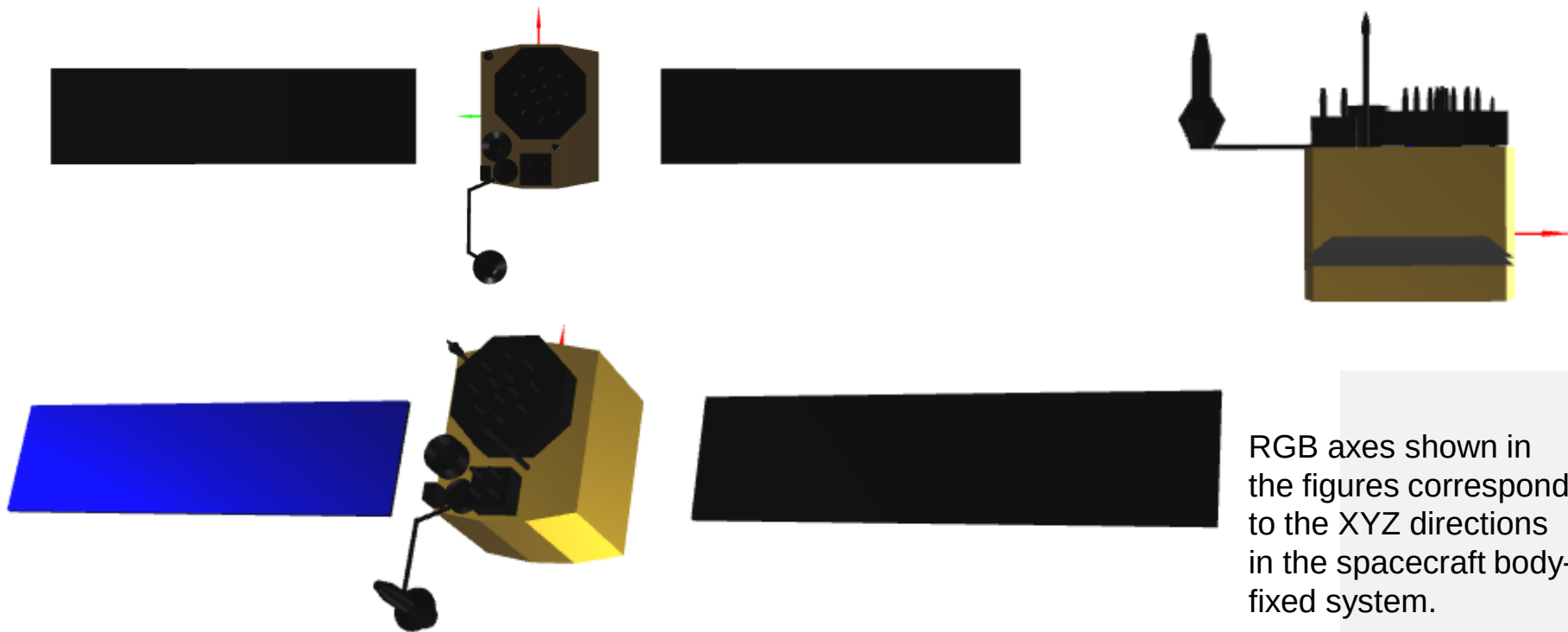


[4]



[5]

Output: Spacecraft Model GPSIIF_v04 +

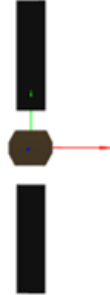
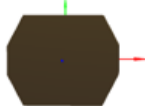


Component 1: Spacecraft model

Process: improvements for next iterations

- Investigation and evaluation of data source for inputs.
- Require the justification of material property values used for the model

Model Name	Number of Components	Number of materials used	Model Caption
GPSIIF_v01	13	2	Initial geometric enhanced box-wing model for capturing geometric shape of bus and panels of GPSIIF.
GPSIIF_v02	13	2	Improved geometric model with correct dimensions (GPSIIF_v01 dimensions were incorrect as technical drawings gave dimensions in inches.)
GPSIIF_v03	111	2	Final geometric model of GPSIIF which includes the instruments on the bus of the satellite.
GPSIIF_v04	107	1	First GPSIIF spacecraft model (excluding the panels) used for computing the radiation force model.

Model Name (iteration)	Version 1 – GPSIIF_v01	Version 2– GPSIIF_v02	Version 3 – GPSIIF_v03	Version 4 – GPSIIF_v04b
+Z face				

Component 2: Computing the Radiation force model



Input: Spacecraft model, mass of spacecraft

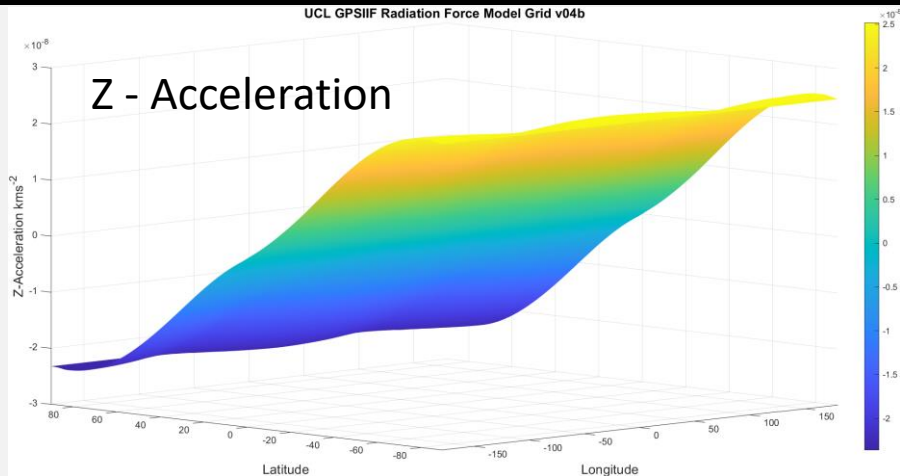


Process: Using python scripts and UCL's high performance computing clusters to produce accelerations for the model



Output: Radiation force model – lookup table of accelerations in the X, Y and Z directions

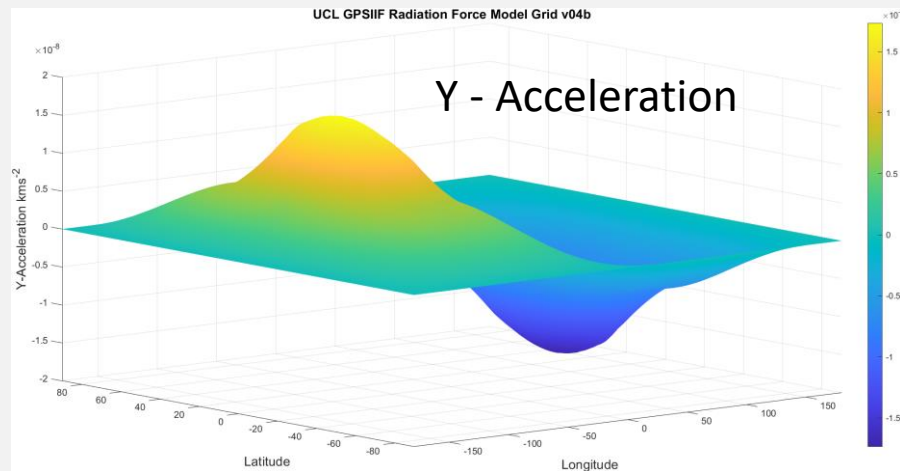
UCL GPSIIF Radiation Force Model Grid v04b



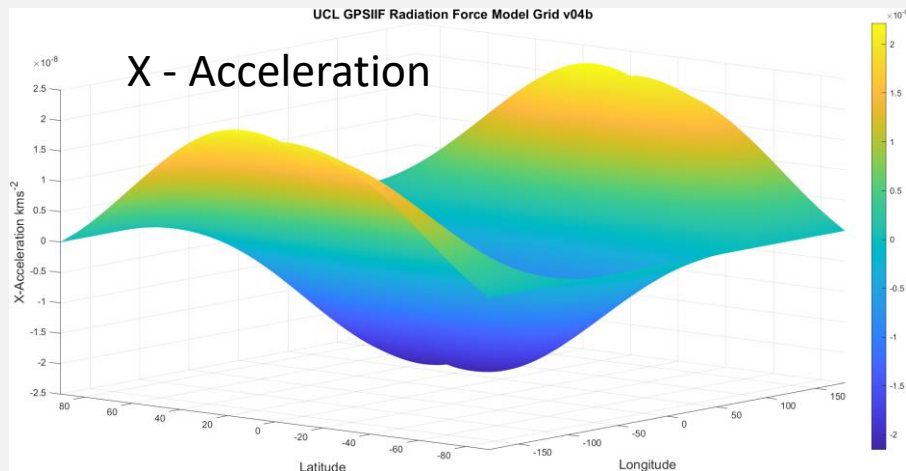
Radiation force model: GPSIIF_v04b

Horizontal axes show longitude and latitude of radiation source. Vertical axis indicates the magnitudes of the accelerations in the X, Y and Z directions.

UCL GPSIIF Radiation Force Model Grid v04b



UCL GPSIIF Radiation Force Model Grid v04b



Preliminary Analysis



Error (m)	3D error	3D max error	Radial	Across-track	Along-track
Without SRP and TRR modelling	60.48	108.75	16.88	4.38	57.89
With SRP and TRR modelling	2.38	5.46	0.82	0.18	2.21

- The metrics shown in the table are conducted through internal tests by UCL as preliminary analysis to show the performance of the model.
- No model is used for the case with SRP?TRR modelling and version 4 of the model is used for the case with SRP/TRR modelling.
- The tests are done by taking initial value of the satellite position from the IGS reference orbit. This is used to propagate the orbit for 12 hours (one orbit period). This is done for all GPS IIF satellites. The analysis period is the full month of March 2020. The predicted orbit is compared against the reference orbit and statistics are computed.
- **GPSIIF_v04** achieved 3D error at the meter level in this test.
- Modelling with SRP and TRR effects lead to a reduction in 3D error by **~25.4 times** when compared to a radiation model with no SRP/TRR modelling.
- Previously successful UCL model – GPS block IIR [1] achieved 3D error at the sub-meter level in this test.
- Therefore, using the GPS block IIR model as a benchmark we look to reduce the errors down to similar levels for the final radiation force model before moving on to the next stages.

Orbit Prediction Tests



- **Tests carried with the UCL Orbit Dynamics Library;** force models produced using the UCL STC
- **Analysis period:** March 2020
- **S/C included:** all GPS IIF s/c on orbit during analysis period
- **Reference Orbit:** IGS final
- **Numerical Integrator:** RK7/8
- **Earth Gravity:** EGM 2008, up to degree and order 20
- **Third-body Gravity:** Sun, Moon and Venus using JPL DE430
- **Radiation Force Modelling:** Grids computed using ray-tracing methods in the UCL STC
- **Antenna Thrust:** 249 W (P. Steigenberger et al, Journal of Geodesy 2018)
- **Mass:** 1633 kg
- **Solar Array:** 22 m^2 ; uses same values as IIR solar array

What Next?



Future steps for the project

- Looking for further insights and suggestions into material properties and testing methods.
- Open to collaboration for POD testing.

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- Santosh Bhattarai: s.bhattarai@ucl.ac.uk

References



- [1] S. Bhattarai, M. Ziebart, S. Allgeier, S. Grey, T. Springer, D. Harrison, and Z. Li, “Demonstrating developments in high-fidelity analytical radiation force modelling methods for spacecraft with a new model for GPS IIR/IIR-M,” *Journal of Geodesy*, vol. 93, no. 9, 2019, issn: 0949-7714. doi: 10.1007/s00190-019-01265-7.
- [2] GPS IIF Satellite Vehicle Dimensions published by the IGS Analysis Centre Coordinator at http://acc.igs.org/orbits/IIF_SV_DimensionsConfiguration.ppt (2015)
- [3] (2014). “Model of GPS satellite, 2014 — Science Museum Group Collection,” Science Museum Group, [Online]. Available: <https://collection.sciencemuseumgroup.org.uk/objects/co8372005/model-of-gps-satellite-2014-model-representation> (visited on 04/07/2021)
- [4] M. Barrett. (Jul. 30, 2014). “Processing to launch a GPS Satellite,” PocketGPSWorld.com, [Online]. Available: <http://www.pocketgpsworld.com/Processing-to-launch-a-GPSatellite-8361.php> (visited on 04/07/2021).
- [5] P. Blau. (2021). “GPS Block IIF – Spacecraft & Satellites,” [Online]. Available: <https://spaceflight101.com/spacecraft/gps-block-iif/> (visited on 04/07/2021).
- [6] M. Y. Gulamali and M. K. Ziebart, “Analytical Solar Radiation Pressure and Thermal Re-radiation Modelling Software,” University College London, Department of Geomatic Engineering, Internal Report Version 5.05, Sep. 29, 2006.
- [7] S. Bhattarai, “EMOTE CCN: Updating the STC s/c userfile format,” UCL, Internal Report Version 6.0, Feb. 27, 2019.
- [8] (2020). “Boeing: Global Positioning System,” Boeing, [Online]. Available: <https://www.boeing.com/space/global-positioning-system/> (visited on 04/07/2021).
- [9] Farres, Ariadna & Folta, David & Webster, Cassandra. (2017). USING SPHERICAL HARMONICS TO MODEL SOLAR RADIATION PRESSURE ACCELERATIONS.