B14

H-2A R/B のライトカーブ観測と光学シミュレーション

Light Curve Observation and Simulation of H-2A R/B

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積極的デブリ除去（Active Debris Removal, ADR）は、危険なデブリから宇宙活動の安全を確保し、持続可能な宇宙開発を実現するために有望な方法の 1 つであるが、デブリを捕獲する場合等、事前にターゲットの姿勢や運動が必要になる場合がある。我々は、ADR のターゲット候補の一つである日本の H-2A ロケットの第 2 段のライトカーブを望遠鏡と CMOS センサーで観測し、2 つの手法によるシミュレーションで再現しています。その 1 つである光学シミュレータは、H-2A R/B のスケールモデルを用い、軌道上の天体の姿勢、運動、太陽方向などを考慮して、地上の望遠鏡で観測した光カーブを再現することができます。これまでのシミュレーションは主にこの方法で行っていたが、1 件あたりの時間がかかるため、多くのケースで実験することはできなかった。もう一つは、CG を使ったライトカーブシミュレーションツールで、ライトカーブの全体的な傾向を調べることで、実験時間を大幅に短縮する方法です。本報告では、遠方の 2 地点で同時に観測されたライトカーブを用いて、この CG によるシミュレーションを行った結果を紹介する。

Active Debris Removal (ADR) is one of the most promising methods for ensuring safety and sustainable space activities from danger of debris. In order to carry out an ADR mission, the attitude and motion of the target must be determined precisely in advance. We are observing the light curve of the second stage of the Japanese H-2A rockets, one of the ADR target candidates, using telescopes and CMOS sensors, and reproducing by a two methods simulation. One method, the optical simulator uses a scale model of the H-2A R/B and can reproduce the light curve as observed by a ground-based telescope, considering the attitude, motion, and sun direction of the object in orbit. Previous simulations were mainly performed in this method, but due to the time required per case, it was not possible to experiment in many cases. The other method is a CG-based light curve simulation tool that can significantly reduce experimental time by examining the overall trend of the light curves. In this report, we present the results of this CG-based simulation using light curves observed simultaneously at two distant sites.

Light Curve Observation and Simulation of H-2A R/B

H-2A R/B のライトカーブ観測と光学シミュレーション

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Abstract

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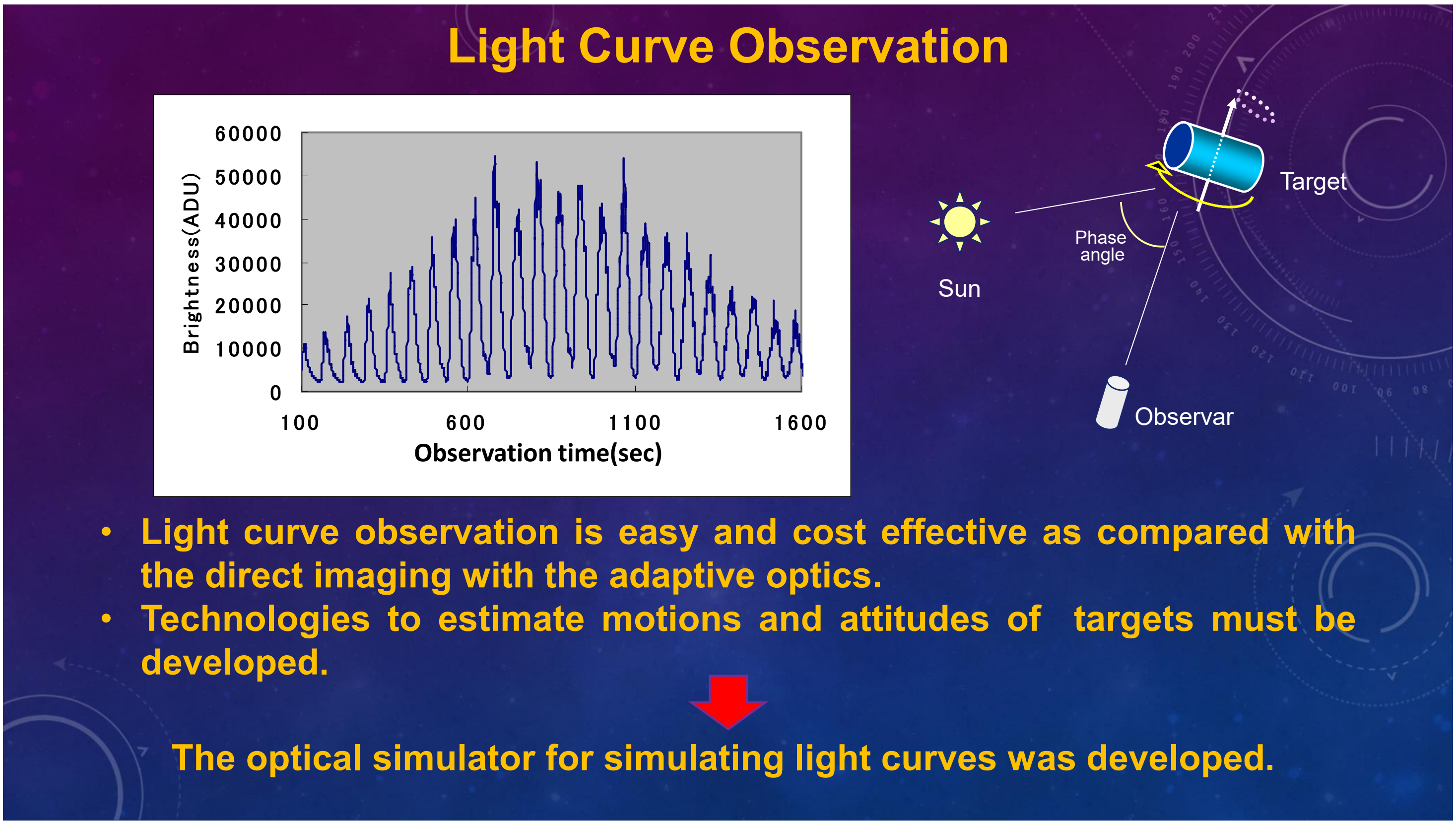
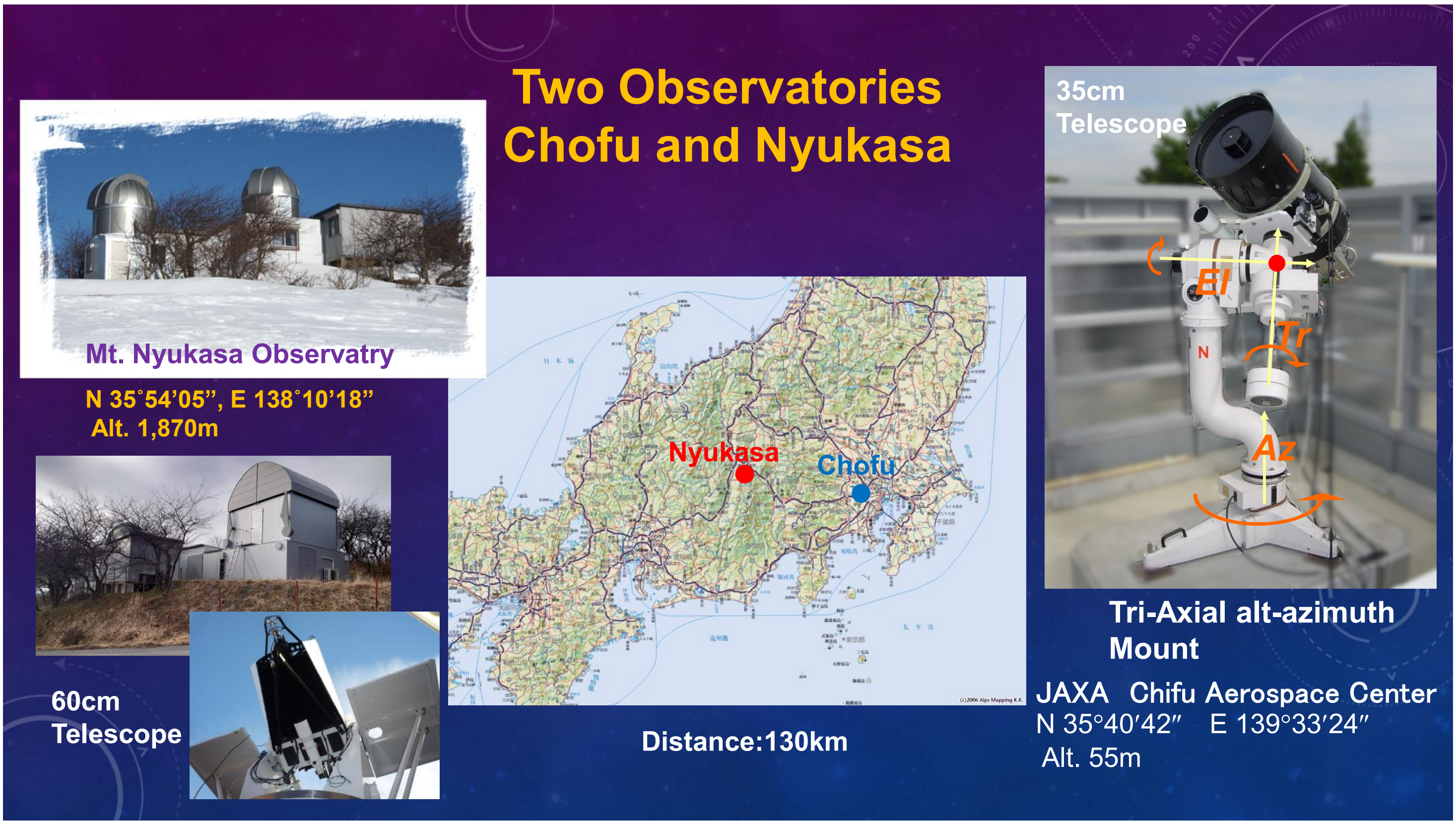


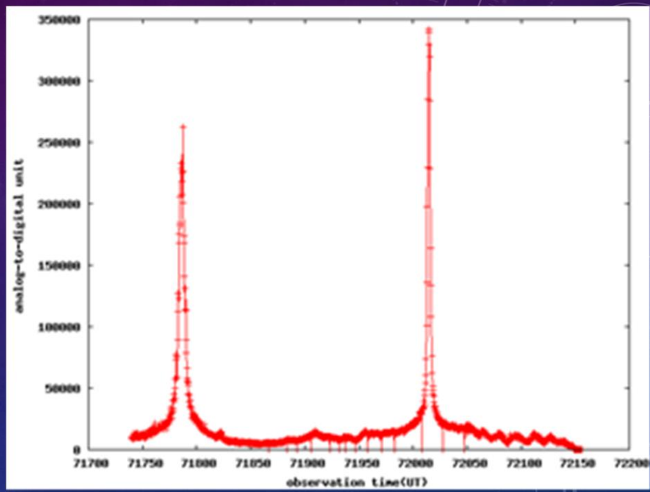
Light Curve Observation
60000
50000
40000
30000
20000
10000
0
Brightness(ADU)
100
600
1100
1600
Observation time(sec)
Target
Phase angle
Sun
Observar
• Light curve observation is easy and cost effective as compared with the direct imaging with the adaptive optics.
• Technologies to estimate motions and attitudes of targets must be developed.
The optical simulator for simulating light curves was developed.



Two Observatories
Chofu and Nyukasa
Mt. Nyukasa Observatry
N 35˚54’05”, E 138˚10’18”
Alt. 1,870m
60cm
Telescope
Nyukasa
Chofu
Distance:130km
35cm
Telescope
El
Tr
Az
Tri-Axial alt-azimuth
Mount
JAXA Chifu Aerospace Center
N 35°40′42″ E 139°33′24″
Alt. 55m

Light curve observations of H-2A R/Bs

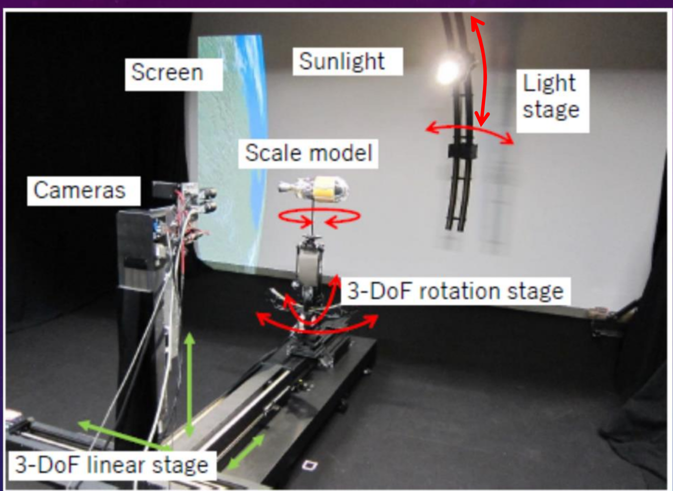
Light curve observations of 4 H-2A R/Bs are being carried out using 60cm telescope



The light curve of 39771 observed on March 19, 2019. Two strong peaks are observable

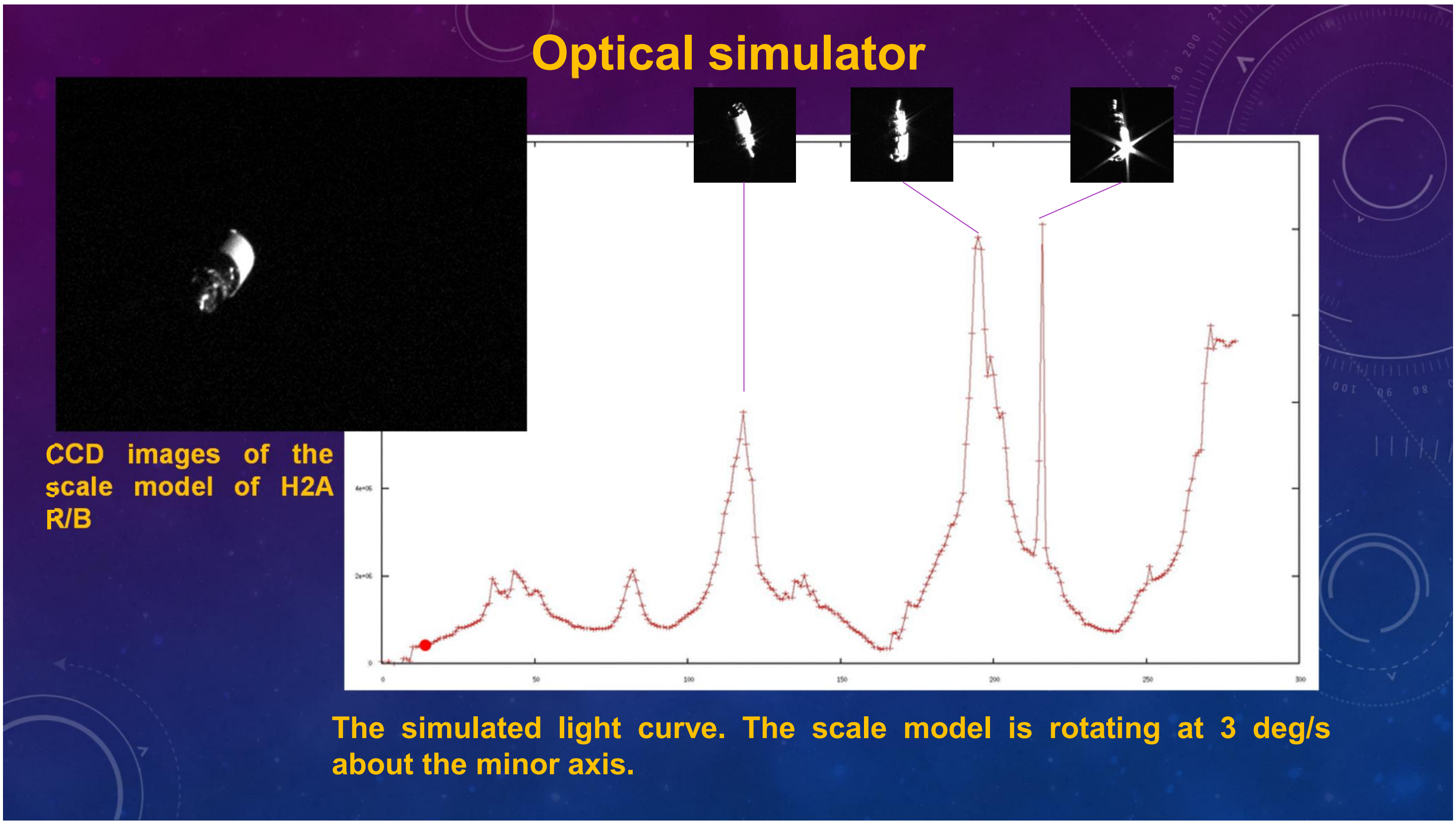
Light curve simulations were carried out using the optical simulator

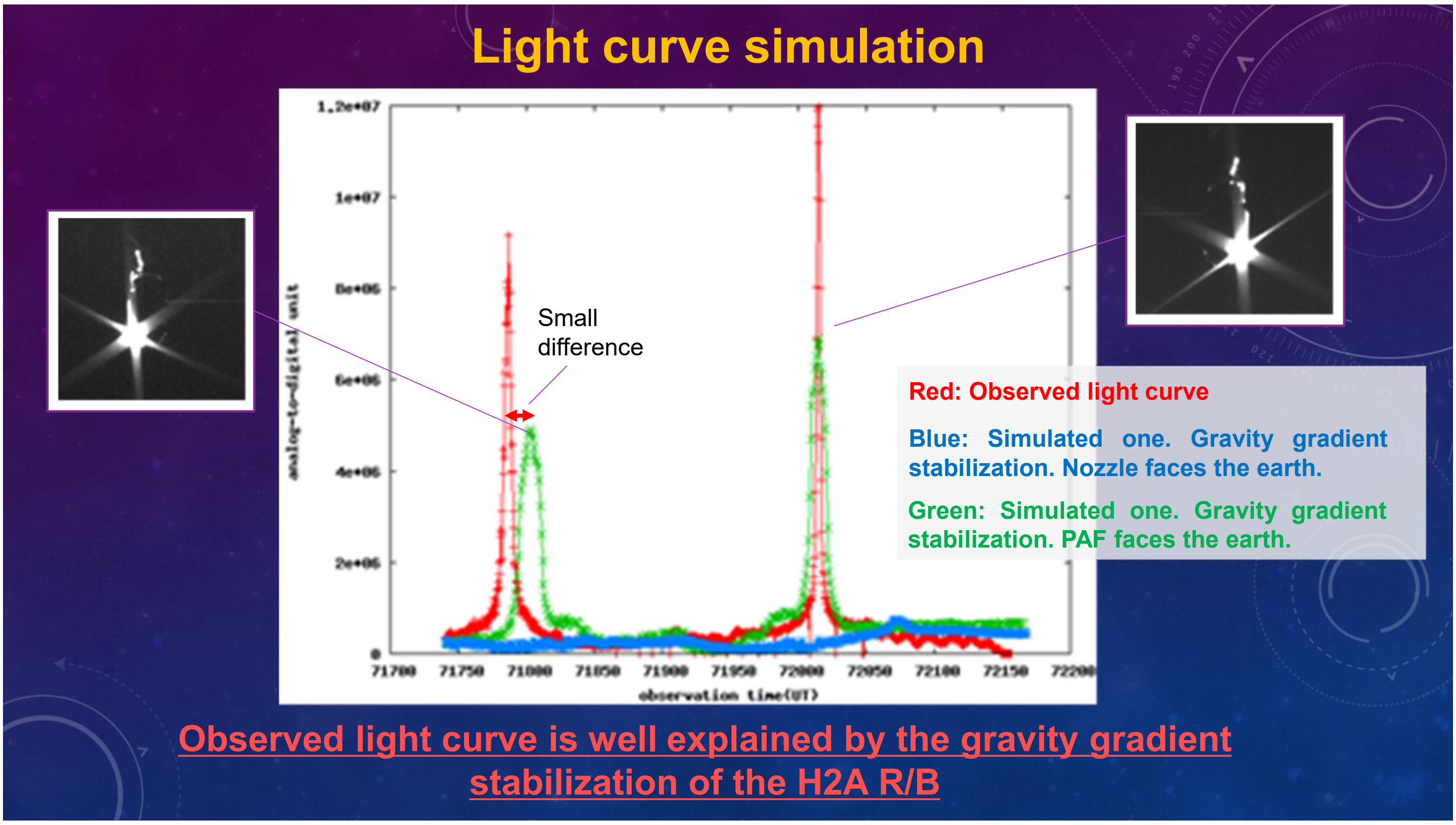
Laboratory optics simulator with scale model



The scale model of H2A R/B

- The optical simulator consists of a 3-DoF (degree of freedom) linear stage, a 3-DoF rotation stage, a light stage, a scale model of the target, and CCD cameras.
- The optical simulator can simulate the orbital environment including lighting condition, attitude and motion of the target.
- Simulated light curve is created analyzing images taken by the CCD camera


Optical simulator
CCD images of the scale model of H2A R/B
The simulated light curve. The scale model is rotating at 3 deg/s about the minor axis.


Light curve simulation
1.2e+07
1e+07
8e+06
6e+06
4e+06
2e+06
0
analog-to-digital unit
71700
71750
71800
71850
71900
71950
72000
72050
72100
72150
72200
observation time(UT)
Small difference
Red: Observed light curve
Blue: Simulated one. Gravity gradient stabilization. Nozzle faces the earth.
Green: Simulated one. Gravity gradient stabilization. PAF faces the earth.
Observed light curve is well explained by the gravity gradient stabilization of the H2A R/B

室内光学シミュレータの弱点
Weakness of laboratory optical simulator

詳細な形状や反射特性の再現が難しい
Difficult to reproduce detailed shapes and reflective characteristics

1つのパターンの実験に時間がかかる
Experiment of one condition takes real time

CG光学シミュレータの利点
Advantages of CG optical simulator

詳細な形状や反射特性を再現できる
Reproduce detailed shapes and reflective characteristics

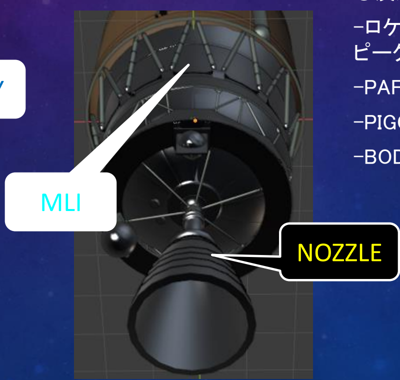
短時間で数多くの条件を解析することが可能
Numerous conditions can be analyzed in a short time

CG Model(H-2A R/B 38341(21号機))

●反射特性＝Phong reflection modelの使用(鏡面反射のみ)
●簡易形状のCGモデルの使用
- 反射特性を大きく6種類に分類
- トラス、PIF、PAF上の機器、パネル、配管(一部除く)の削除
- タンクを除くエンジンマウントリング上の機器削除
- ノズルスカート以外のエンジン部の機器、配管の削除
- MLIのしわの除去

Reflective characteristics = Phong reflection model (Mirror reflection only)
CG models of simple shapes
・Six major categories of reflective characteristics
・Removal of equipment, panels, and piping on trusses, PIFs, and PAFs (except for some)
・Removal of equipment on engine mounts and rings (except tanks)
・Removal of equipment and piping on engine sections except nozzle skirts
・Wrinkle removal on MLI

PAF side



Nozzle side

●反射強度：試験結果に基づいた反射強度
- ロケット上段表面素材特性評価のBRDF計測結果の最も反射率のピークの高いPSSを1として、各パーツのピークの比率を強度に設定
- PAF、MLIは計測結果からの比率をそのまま設定
- PIGGY、NOZZLは、Adapterの計測結果からの比率を仮設定
- BODY(PIF)は、別途報告された経年劣化(80～90%減)を反映

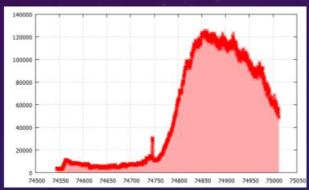
	解析画像1鏡面反射特性	強度	光沢度	☑ 解析画像2鏡面反射特性	強度	光沢度
R	PSS	1.00000	1000.0	NOZZL	0.26000	400.0
G	PAF	0.11000	100.0	MLI	0.44000	800.0
B	PIGGY	0.26000	200.0	BODY	0.00018	1.0

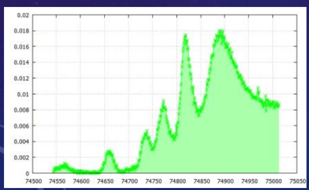
形状マッチングによる解候補の探索
Search for solution candidates by shape matching

●標準化
・サンプリング時刻=1.0[s]
・観測時間帯のライトカーブ面積=100
●評価値(F)
・観測時間での観測値と解析値の差(絶対値)の合計
⇒小さくなるデブリ姿勢の解析条件を解候補

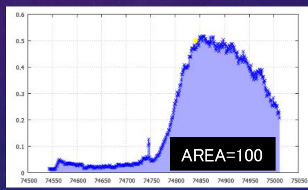
● Standardization
・Sampling Time = 1.0s
・Light curve area during observation time = 100
●Evaluation value（F）
Sum of the difference (absolute value) between observed and analyzed values at the observation time
→The analysis condition for the smaller debris attitude is taken as a solution candidate.

F=$\sum_S^E \| Observation\ val. - Analysis\ val. \|$
→ min

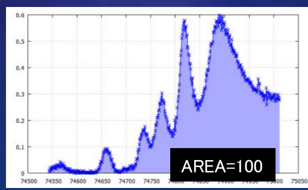

Light curves by observation


Light curves by analysis

Standardization
標準化

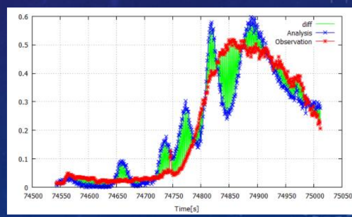


after standardization



after standardization

Evaluation value
評価値

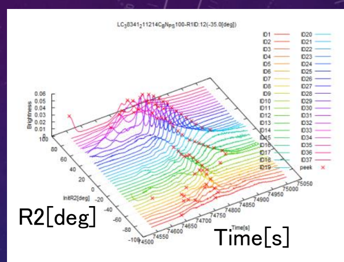


解候補探索のStep
Steps in Solution Candidate Search

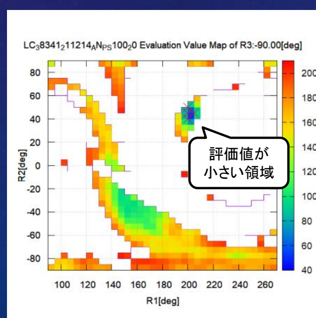
●Step1:
網羅解析：観測開始時のデブリ姿勢角条件を全範囲で粗いステップで変更
−面内姿勢角(R1)(2通り)：
・PAF地心方向基準(PAF基準)：180[deg]±90[deg] ステップ：5[deg]
・ノズル地心方向基準(ノズル基準)：0[deg] ±90[deg] ステップ：5[deg]
−面外姿勢角(R2)：−90[deg]～90[deg] ステップ：5[deg]
−デブリ円筒軸回り姿勢角(R3)：−90[deg]～90[deg] ステップ：30[deg]
全解析数：9583通り
⇒評価値の小さな解析条件の領域で次ステップの解候補探索範囲を限定。

Exhaustive analysis:
- In-plane attitude angle (R1)
・PAF geocentric direction reference : 180±90 deg. step:5deg.
・Nozzle geocentric direction reference : 0±90 deg. step:5deg.
- Out-of-plane attitude angle:(R2) : -90~+90deg. step:5deg.
- Attitude angle around cylindrical axis (R3) -90~+90deg. step:5deg.
→Limit the range of candidate solution search in the next step in the region of analysis conditions with small evaluation values.

●Step2以降:
−前Stepで限定された解析条件の範囲でより細かいステップの網羅解析
−範囲がある程度限定されたところで、角速度条件を範囲に含めた網羅解析



−Step1 Light Curve Analysis−
In−plane(R2) −90deg～90deg: Step 5deg



−Step1 Evaluation values map−
横軸：面内角(R1),縦軸：面外角(R2)の評価値をマップ化

解析ケース(2地点、2日)

Analysis Case (2 Sites, 2days)

●**Analysis**

−Case1:

Chofu:Start time:2021.12.14 20:42:47(74567s)(UT) Observation time: 366s

Nyukasa: Start time :2021.12.14 20:42:24(74544s)(UT) Observation time: 469s

−Case2: (after 6 days)

Chofu : Start time :2021.12.20 20:42:17(74537s)(UT) Observation time: 365s

Nyukasa : Start time :2021.12.20 20:41:42(74502s)(UT Observation time: 472s

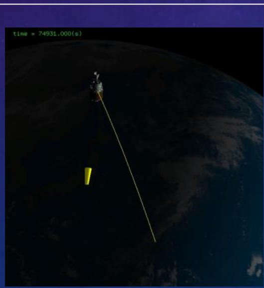
Case1:TLE

```
0 H-2A R/B
1 38341U 12025E   21347.57744250  .00000204  00000-0  31373-4 0  9997
2 38341  98.5193 185.3194 0054097 284.5746  74.9470 14.84345241518076
```

Case2:TLE

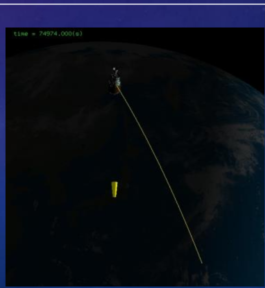
```
0 H-2A R/B
1 38341U 12025E   21354.52068479  .00000830  00000-0  10402-3 0  9996
2 38341  98.5188 192.7341 0054042 261.7872  97.7209 14.84354256519185
```

at Nyukasa



at Chofu

Case 1



at Nyukasa

at Chofu

Case 2

Step1 解析結果例

Example of Analysis Result

●評価値ランキングTOP20(評価値の昇順) Top 20 evaluation value ranking

・PAF基準:ほぼ同じ領域(R1:200[deg]、R2:40[deg]付近に上位ランクの解析条件が存在

・ノズル基準:ノズル地心方向(R1=R2=0.0[deg])に近い解析条件がランキング上位を占める

・PAF criteria: Top ranked analysis conditions exist near approximately the same area (R1:200deg R2:40deg)

・Nozzle criteria: conditions close to nozzle geocentric direction (R1=R2=0.0deg)

−Case1−

PAF基準

Rank	Total	調布	入笠	R1[deg]	R2[deg]	R3[deg]
1	41.469	22.831	18.639	205	45	0
2	42.167	21.164	21.003	205	45	30
3	43.205	20.873	22.332	200	45	30
4	45.370	19.214	26.156	200	45	90
5	45.616	20.124	25.492	200	45	−90
6	46.503	24.006	22.497	205	45	−90
7	46.957	21.547	25.410	205	45	90
8	47.483	28.490	18.993	200	50	−60
9	48.074	23.405	24.669	200	45	−60
10	48.856	35.833	13.023	200	40	90
11	48.999	33.229	15.771	200	50	−90
12	49.144	27.667	21.477	200	50	30
13	49.186	21.165	28.021	200	45	0
14	49.900	23.652	26.248	205	45	−60
15	50.375	37.612	12.763	200	40	−90
16	50.392	33.728	16.664	200	40	60
17	50.504	33.253	17.251	205	40	−60
18	51.134	26.168	24.967	200	40	−60
19	51.533	38.521	13.012	200	40	0
20	53.165	32.040	21.125	200	50	90

Nozzle基準

Rank	Total	調布	入笠	R1[deg]	R2[deg]	R3[deg]
1	39.276	19.650	19.626	−5	−5	90
2	39.704	21.244	18.460	−5	0	0
3	41.921	26.748	15.173	0	0	90
4	42.616	21.603	21.014	−5	0	−60
5	43.080	20.859	22.220	−5	0	−90
6	43.208	21.995	21.213	−5	0	90
7	44.118	23.701	20.417	−5	0	30
8	46.348	21.761	24.586	−10	−5	−60
9	46.930	21.646	25.284	−5	0	−30
10	47.014	27.308	19.706	0	0	−30
11	47.306	23.951	23.356	0	5	0
12	47.518	23.440	24.078	−5	−5	−90
13	48.201	25.857	22.344	−5	0	60
14	49.253	25.396	23.857	0	0	60
15	49.342	21.072	28.271	−5	−5	60
16	49.353	23.594	25.759	−20	−20	0
17	49.356	27.523	21.832	0	5	−60
18	49.389	26.139	23.250	−5	5	−30
19	50.351	23.409	26.942	−10	−5	−90
20	50.375	27.414	22.962	0	5	60

−Case2−

PAF基準

Rank	Total	調布	入笠	R1[deg]	R2[deg]	R3[deg]
1	32.572	15.554	17.018	200	45	−60
2	34.222	18.807	15.415	205	45	0
3	35.013	15.015	19.998	200	45	30
4	36.669	18.559	18.110	205	45	30
5	36.937	16.867	20.069	205	45	−60
6	43.506	12.959	30.547	200	45	−90
7	43.903	25.870	18.033	200	40	60
8	44.105	19.846	24.259	205	45	−90
9	44.268	17.166	27.102	205	45	90
10	45.078	21.030	24.049	200	40	−60
11	45.155	13.411	31.744	200	45	90
12	47.713	30.027	17.686	205	40	−60
13	48.000	28.458	19.542	200	40	30
14	48.201	28.490	19.711	200	40	90
15	49.297	31.641	17.656	200	40	−90
16	50.980	20.575	30.404	200	45	0
17	51.083	18.418	32.664	200	45	60
18	52.303	32.479	19.824	200	50	−90
19	52.930	21.341	31.589	200	45	−30
20	54.228	31.307	22.921	200	50	90

Nozzle基準

Rank	Total	調布	入笠	R1[deg]	R2[deg]	R3[deg]
1	38.425	17.604	20.821	−5	0	−30
2	40.110	18.689	21.421	−5	0	90
3	40.962	20.047	20.915	−5	−5	90
4	41.076	19.031	22.045	−5	0	−90
5	41.509	19.513	21.997	−5	0	−60
6	42.985	21.331	21.655	−45	−30	30
7	43.317	23.861	19.456	−20	−10	0
8	43.554	20.766	22.788	−5	−5	−30
9	43.641	23.348	20.293	−45	−30	−30
10	44.071	20.475	23.596	−20	−15	0
11	44.440	22.993	21.447	−5	0	60
12	46.213	24.611	21.603	−10	−10	90
13	46.423	24.104	22.319	0	0	60
14	47.195	19.839	27.356	−45	−30	−60
15	47.699	29.139	18.560	−40	−15	−60
16	47.798	31.346	16.451	−45	−35	30
17	48.003	23.132	24.871	−5	−5	−90
18	48.365	28.563	19.802	−40	−15	30
19	48.912	27.774	21.138	−40	−10	30
20	49.052	25.166	23.886	−20	−10	60

Step1 解析結果／評価例

Step 1 Example of Analysis Result

●Case1とCase2の評価値マップ比較(反射パターンB)

－異なる日(6日後)で、ほぼ同じマップのパターン

⇒デブリの姿勢変化が小さい、

あるいは、周期的運動で偶然に姿勢が一致？

Comparison of evaluation value maps of Case1 and Case2 (reflection pattern B)

- Different days (6 days later), almost the same map pattern

→Debris attitude change is small, Coincidence of Posture in Periodic Motion?

－デブリが重力傾斜安定で姿勢変動が小さい

⇒評価値が小さい領域となるノズル地心方向付近で重力傾斜安定の可能性が高

- Debris is stable due to gravity tilt and attitude fluctuation is small

→The possibility of gravity tilt stability is high near the nozzle geocenter direction, where the evaluation value is small

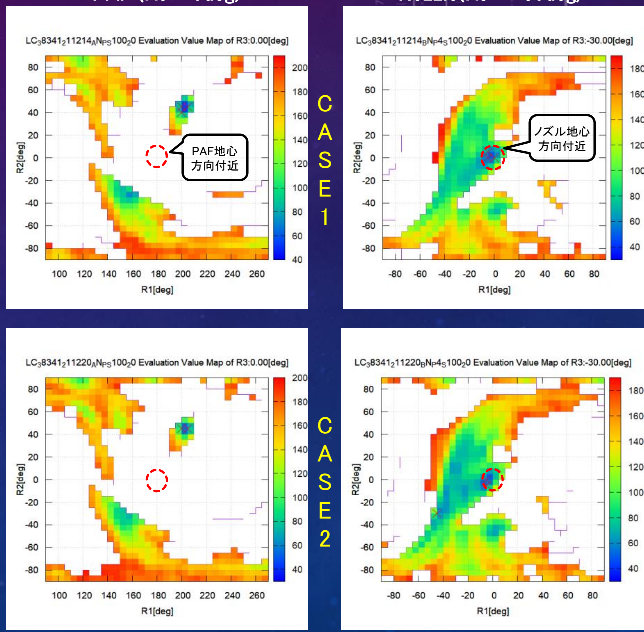
－Step2以降

⇒ノズル地心方向近傍での探索を実施

→Search near nozzle geocentric direction

－Step1 Evaluation value maps－

－PAF (R3 = 0deg)－ －Nozzle(R3 = −30deg)－



Step1 解析結果／評価例

Step 1 Example of Analysis Result

●PAF地心方向の重力傾斜安定でのライトカーブ解析結果(解析例：CASE1の調布観測)

－PSSの鏡面反射特性が支配的なライトカーブとなる

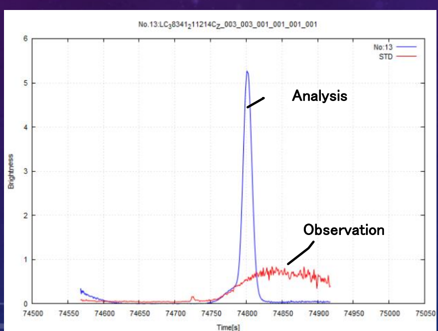
→本観測結果でのデブリのPAF地心方向での重力傾斜安定の可能性は極めて低い

Light curve analysis results with gravity tilt stability in the PAF geocentric direction

- Specular reflection characteristics of PSS dominates the light curve

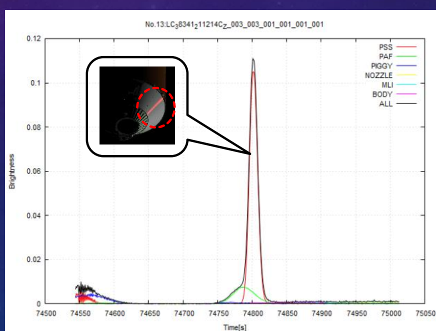
→The possibility of gravity tilt stability of debris in the direction of the PAF geocenter in this observation is extremely low

－標準化ライトカーブの比較－



Comparison of standardized light curves

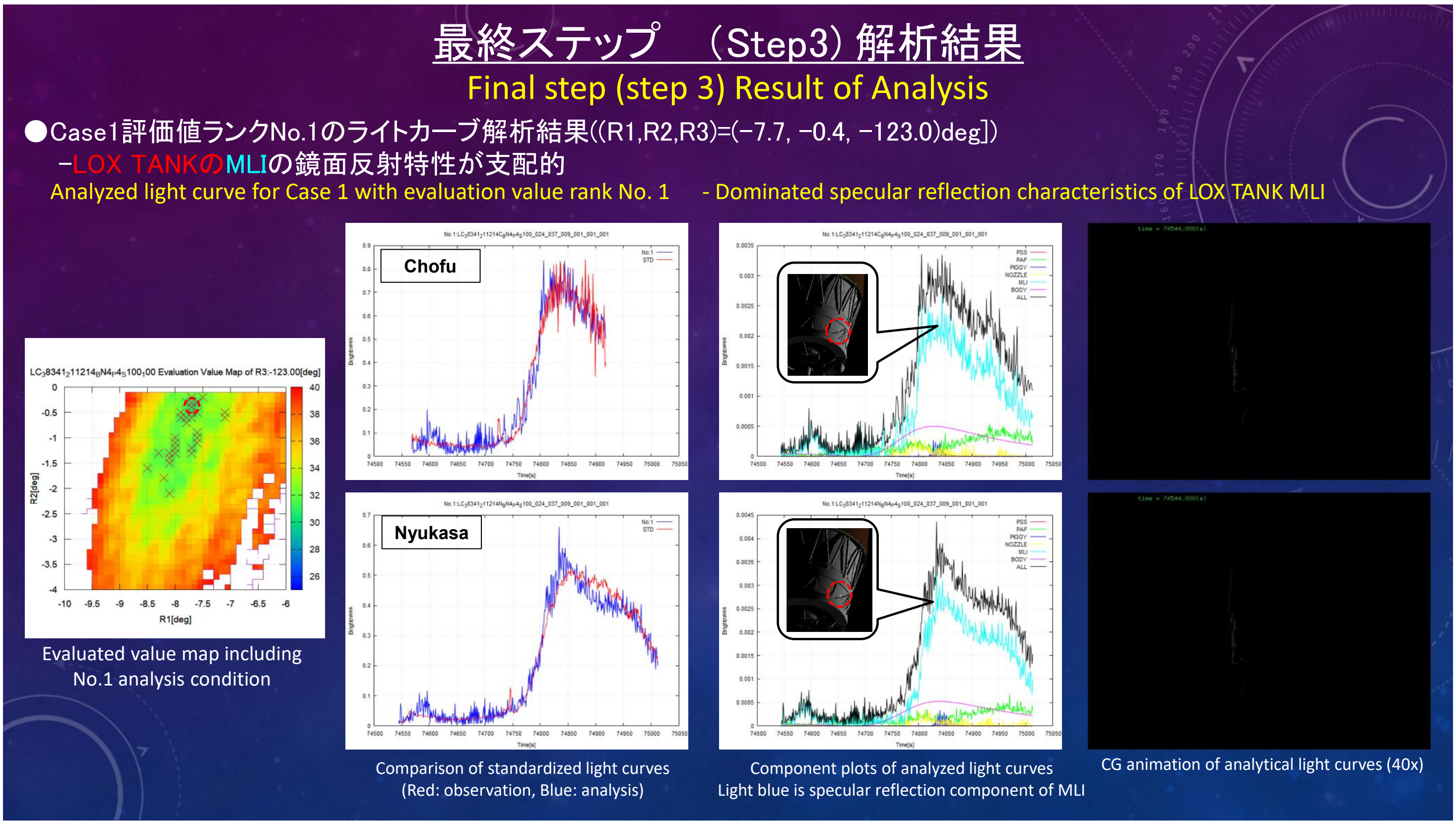
－解析ライトカーブの成分プロット－
（赤がPSSの鏡面反射成分）

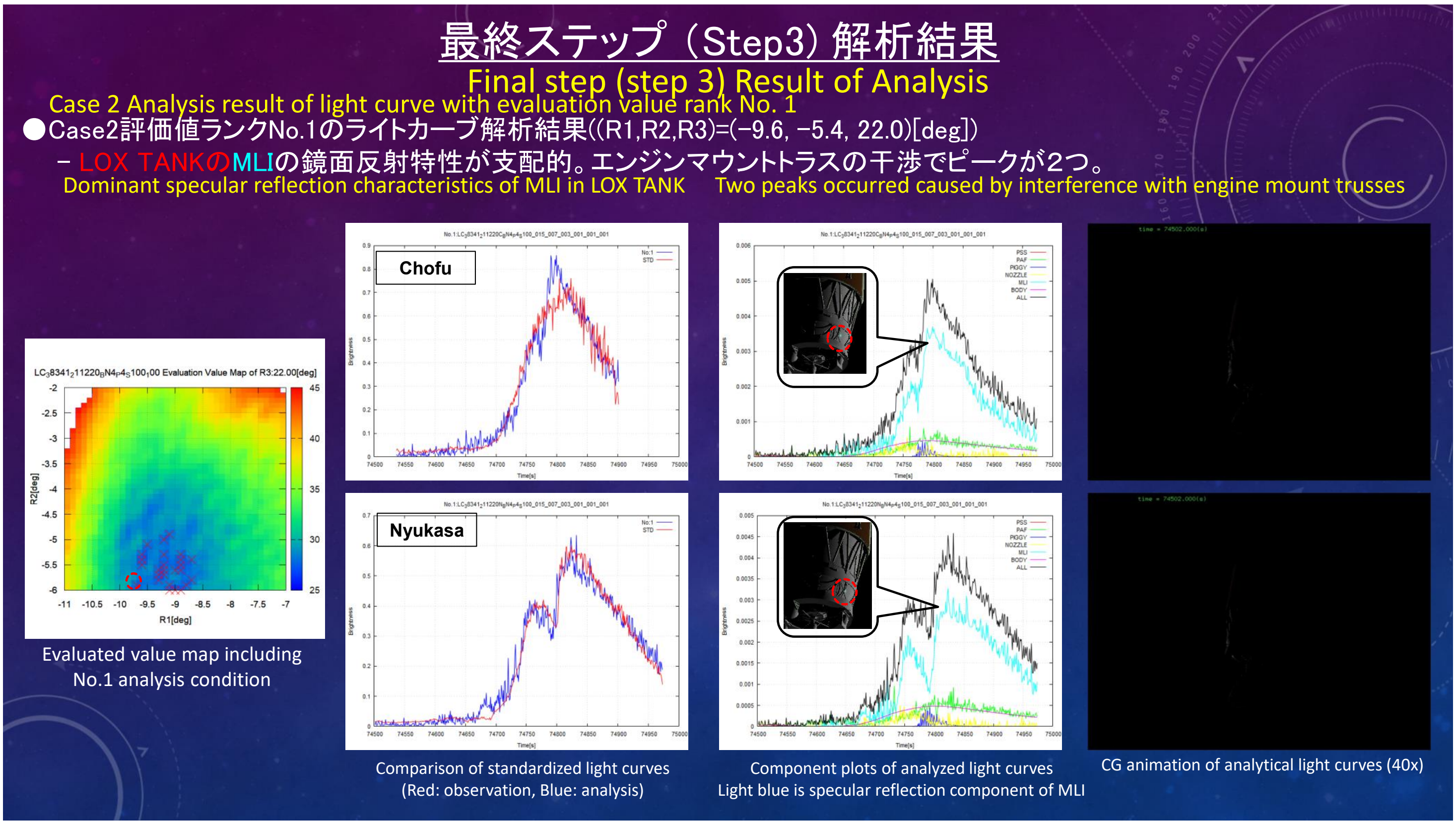


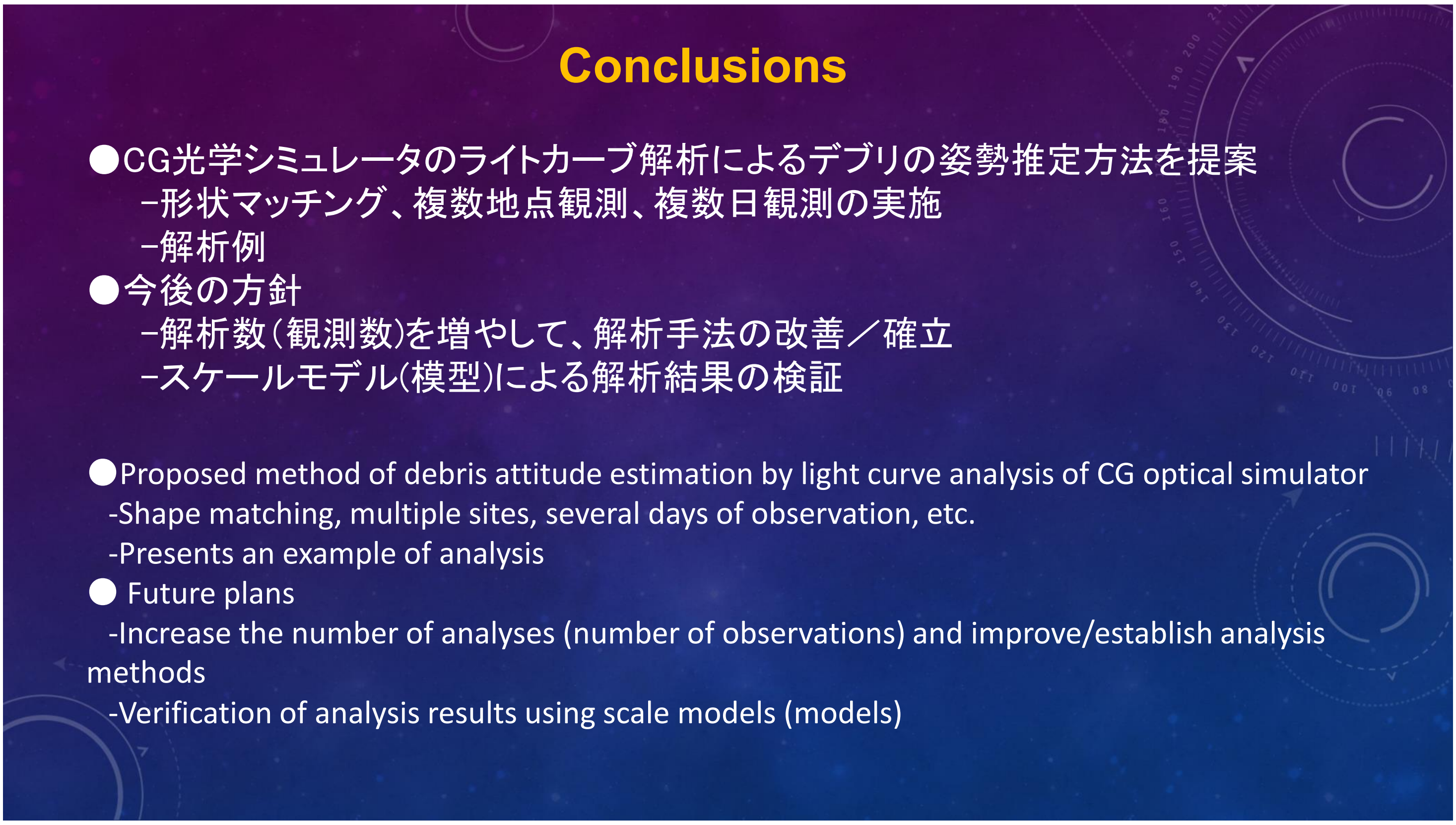
Component plots of analytical light curves
(Red is specular reflection component of PSS)

－解析ライトカーブのCG動画(40倍)－
（赤がPSSの鏡面反射成分）

CG animation of analytical light curve (40x)
(Red is specular reflection component of PSS)


最終ステップ　（Step3）解析結果
Final step (step 3) Result of Analysis
●Case1評価値ランクNo.1のライトカーブ解析結果((R1,R2,R3)=(−7.7, −0.4, −123.0)deg])
−LOX TANKのMLIの鏡面反射特性が支配的
Analyzed light curve for Case 1 with evaluation value rank No. 1　- Dominated specular reflection characteristics of LOX TANK MLI
Chofu
Nyukasa
Evaluated value map including No.1 analysis condition
Comparison of standardized light curves (Red: observation, Blue: analysis)
Component plots of analyzed light curves Light blue is specular reflection component of MLI
CG animation of analytical light curves (40x)


最終ステップ（Step3）解析結果
Final step (step 3) Result of Analysis
Case 2 Analysis result of light curve with evaluation value rank No. 1
●Case2評価値ランクNo.1のライトカーブ解析結果((R1,R2,R3)=(−9.6, −5.4, 22.0)[deg])
−LOX TANKのMLIの鏡面反射特性が支配的。エンジンマウントトラスの干渉でピークが2つ。
Dominant specular reflection characteristics of MLI in LOX TANK　Two peaks occurred caused by interference with engine mount trusses
Chofu
Nyukasa
Evaluated value map including No.1 analysis condition
Comparison of standardized light curves (Red: observation, Blue: analysis)
Component plots of analyzed light curves Light blue is specular reflection component of MLI
CG animation of analytical light curves (40x)


Conclusions
●CG光学シミュレータのライトカーブ解析によるデブリの姿勢推定方法を提案
−形状マッチング、複数地点観測、複数日観測の実施
−解析例
●今後の方針
−解析数（観測数)を増やして、解析手法の改善／確立
−スケールモデル(模型)による解析結果の検証
●Proposed method of debris attitude estimation by light curve analysis of CG optical simulator
-Shape matching, multiple sites, several days of observation, etc.
-Presents an example of analysis
● Future plans
-Increase the number of analyses (number of observations) and improve/establish analysis methods
-Verification of analysis results using scale models (models)