天津大学
Tianjin University

天文信息学与虚拟天文台
2022年学术年会

分布式时域巡天望远镜阵
调度模式研究

天津大学
张雅洁

智能与计算学部
COLLEGE OF INTELLIGENCE AND COMPUTING

广西 · 桂林
2023年4月

主要内容

CONTENTS

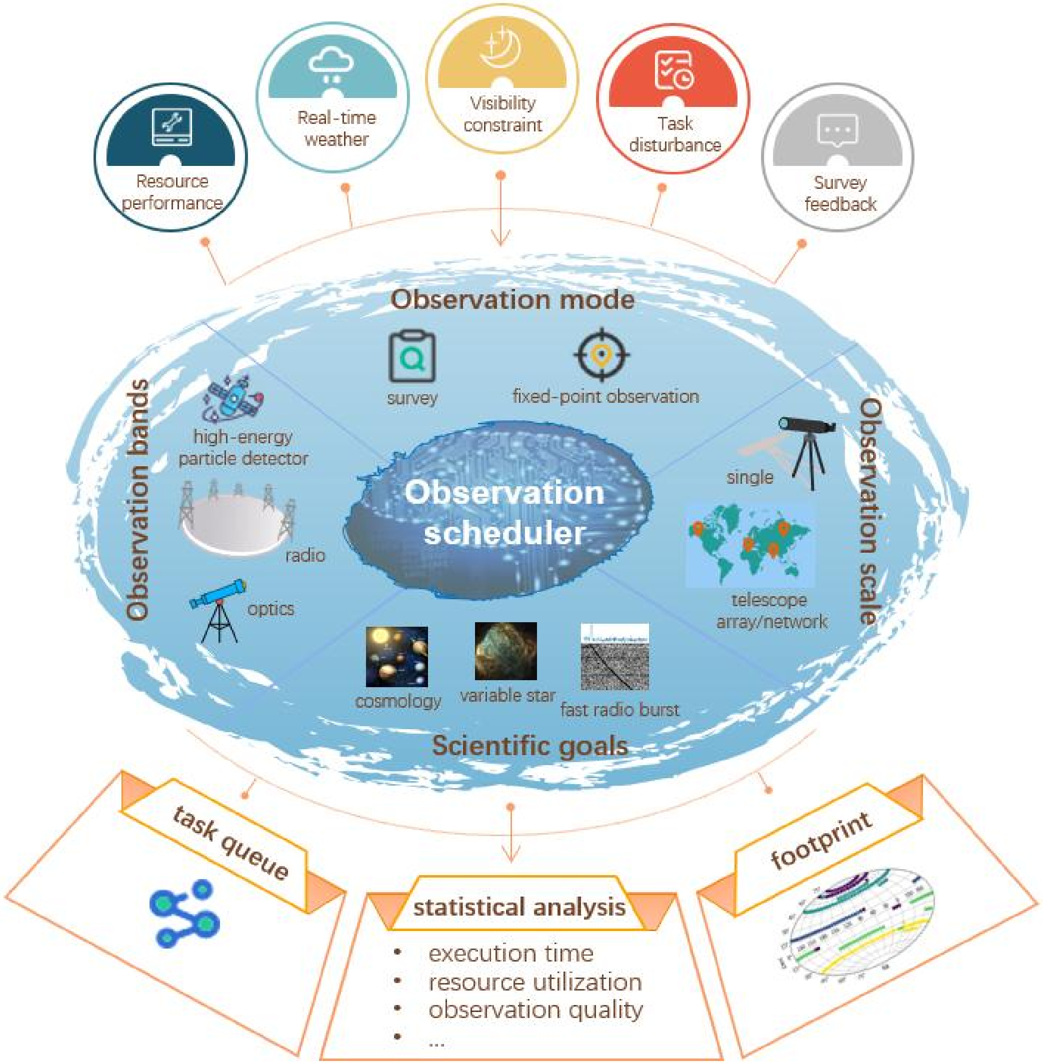
01 背景意义

天文观测:

- 在实际观测中，由于地球自转和公转引起的天体视运动的变化，使得**观测目标在不同季节具有不同的能见度**。
- 天文观测设施**昂贵且寿命有限**。所以**望远镜的观测时间**是一种宝贵而有限的资源，有效安排观测时间对最大限度地科学产出至关重要。

现有时域巡天项目不足:

- 单台望远镜**视场受限**
- 巡天**时间间隔较长** (cadence)
- 无法观测短于**天时标**的时域变化



Ce Yu, Yajie Zhang, Chao Sun, Yi Hu, Zhaohui Shang, and Junhan Ju. 2023. Scheduling techniques in astronomical observation: Survey, taxonomy, challenges, and future trends.

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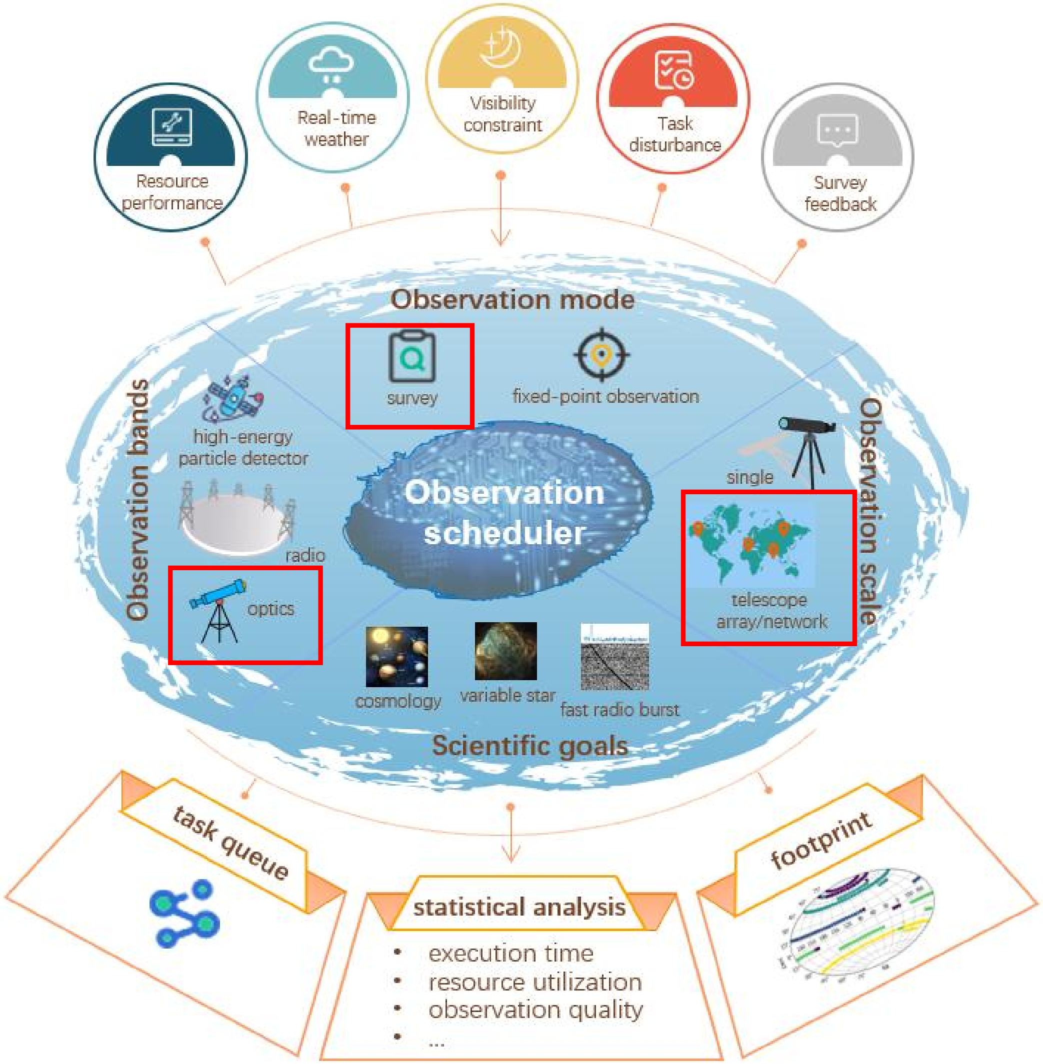

- execution time
- resource utilization
- observation quality
- …

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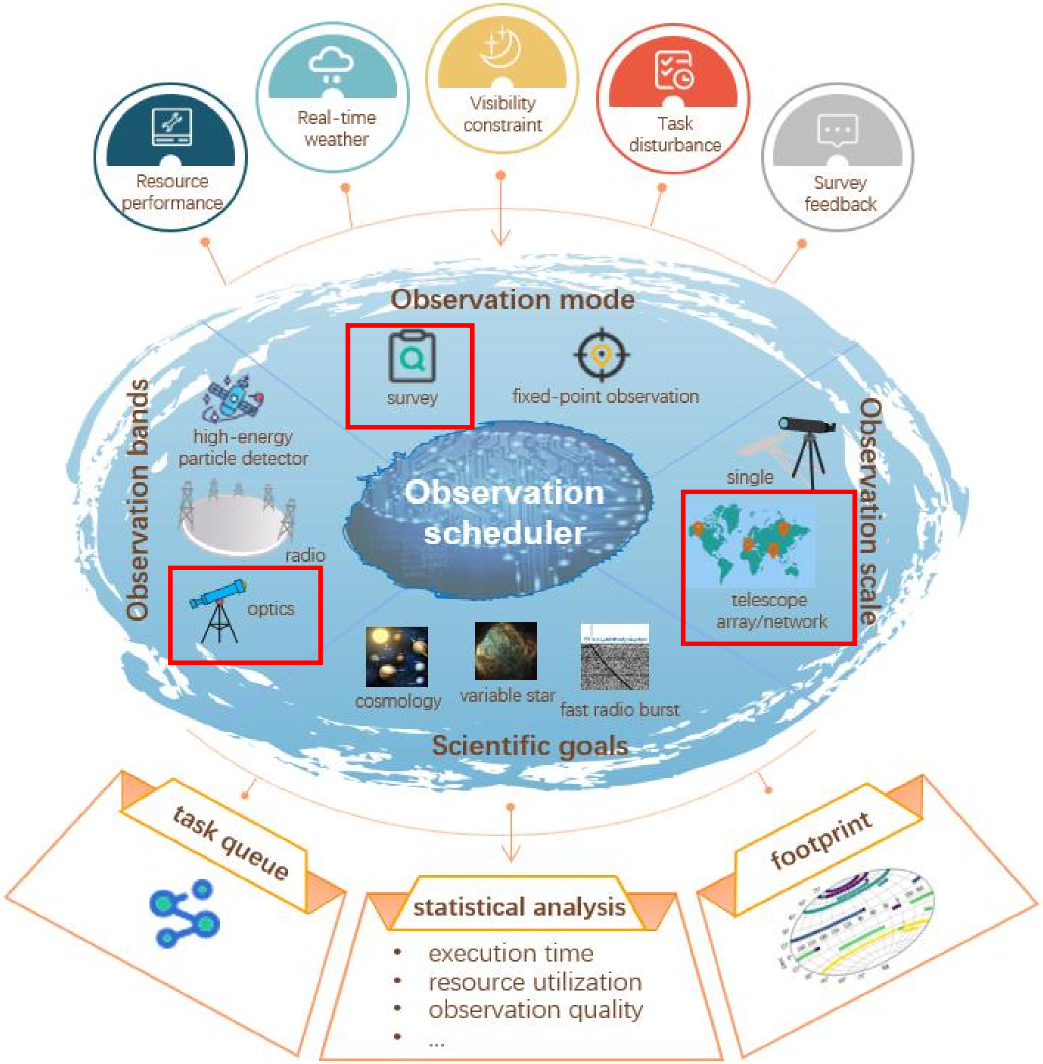
望远镜组阵组网是未来光学时域巡天的必然选择



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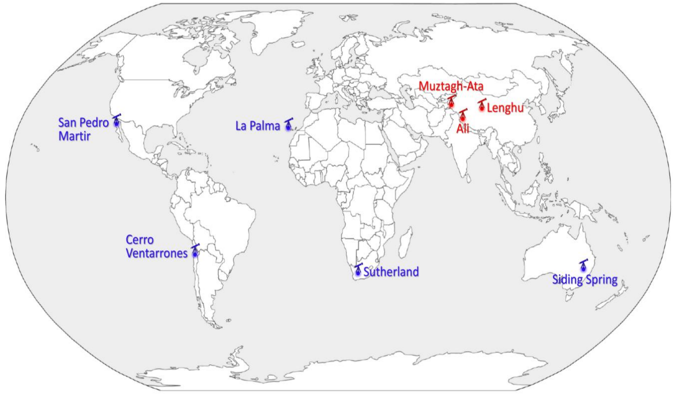
基于望远镜阵的时域观测

- 协同分布于**异地**的多台望远镜的**组阵**观测
- “**大天区、多波段、高频次**”的时域巡天成为可能
- 能够缩短观测时间间隔，保持巡天面积并降低望远镜运行的成本



我国司天工程的初步布局

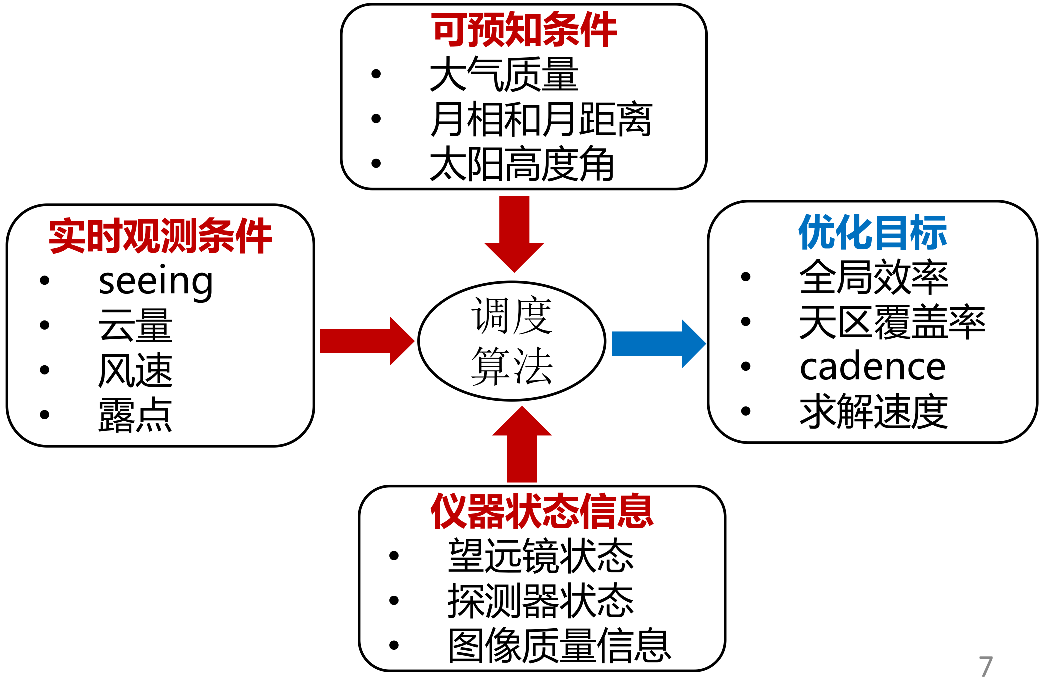
光学时域望远镜阵观测调度

➢ **问题定义**

- 时间变化的不确定约束条件下的多目标优化问题

➢ **原则**

- 时域天文学追求**巡天效率**和**极限星等**
- 在**众多约束条件**下，求解最优的望远镜观测调度方案
- 实时**高效**调度巡天观测，尽量减少无效时间（overheads）



可预知条件
- 大气质量
- 月相和月距离
- 太阳高度角

实时观测条件
- seeing
- 云量
- 风速
- 露点

调度算法

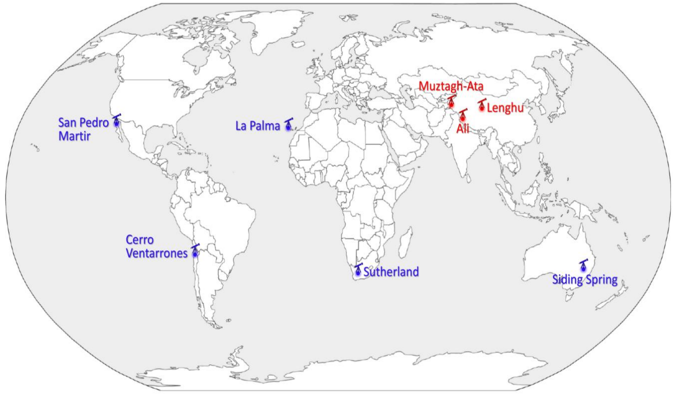
优化目标
- 全局效率
- 天区覆盖率
- cadence
- 求解速度

仪器状态信息
- 望远镜状态
- 探测器状态
- 图像质量信息

基于望远镜阵的时域观测

- 协同分布于**异地**的多台望远镜的**组阵**观测
- “**大天区、多波段、高频次**”的时域巡天成为可能
- 能够缩短观测时间间隔，保持巡天面积并降低望远镜运行的成本

□ 可靠、高效的智能调度方法是构建望远镜阵的核心部分



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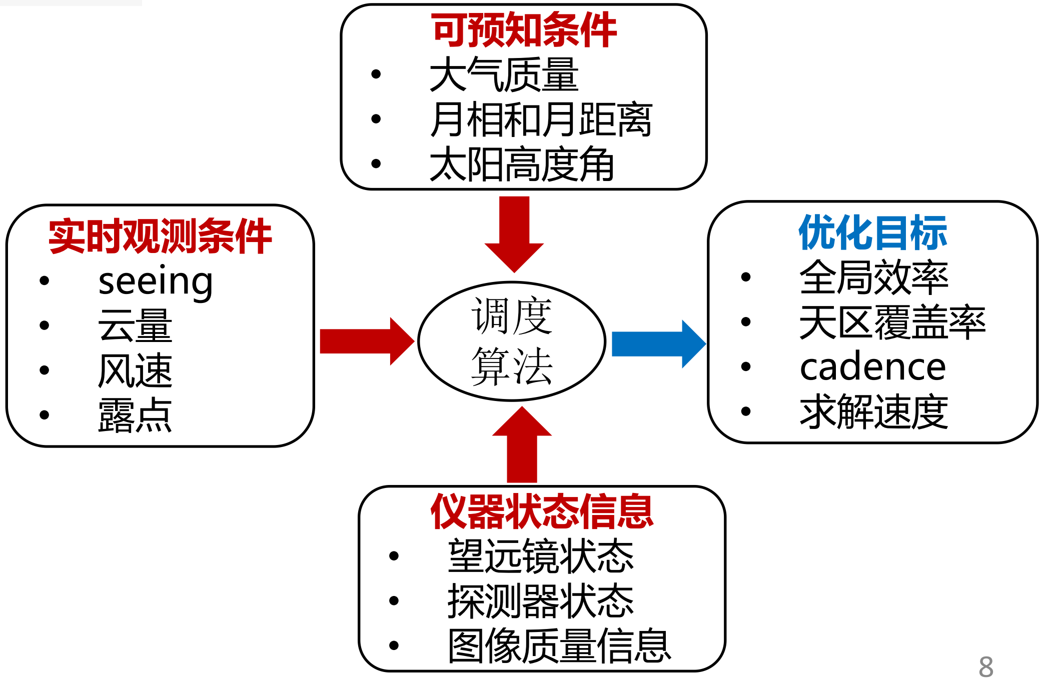

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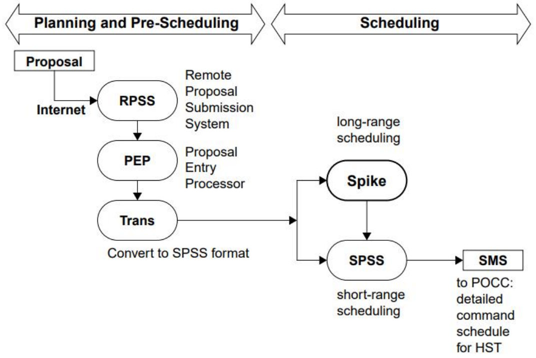
02 研究现状

1) 空间望远镜 - 哈勃望远镜



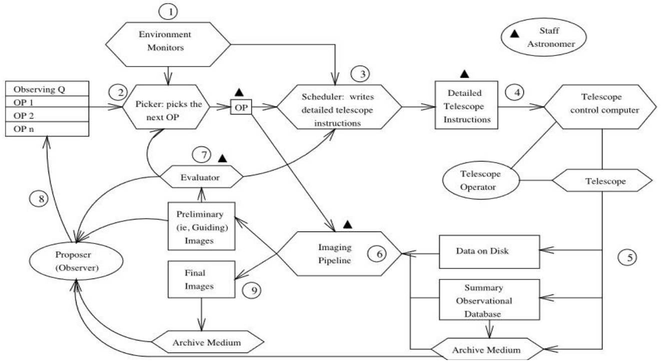
- Spike系统，迭代修正搜索算法

2) 光学时域望远镜 - LSST、ZTF

$$\max\left(\left(\sum_{r\in R}\sum_{t\in T}\sum_{f\in F} V_{rtf}\,Y_{rtf}\right)-\left(\frac{t_{\text{filt}}}{t_{\text{exp}}+t_{\text{OH}}}w\sum_{t\in T} Y_s\right)\right)$$

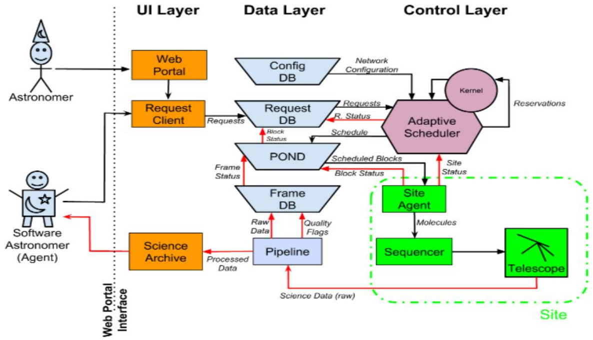
- 基于特征的调度，用到了整数线性规划、时间差分学习和进化算法
- 仅面向**单**望远镜观测调度

3) 射电望远镜网络 - ALMA



- 基于模拟退火和动态规划

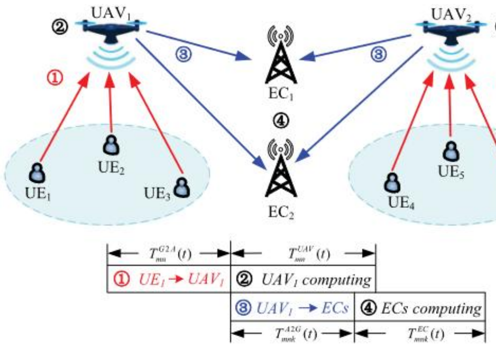
4) 程控自主天文台网络 - LCOGT、GLORIA



- 整数线性规划，基于**观测请求**的调度
- 已具备协调控制全球望远镜观测网络的能力，但仍需很多人工介入

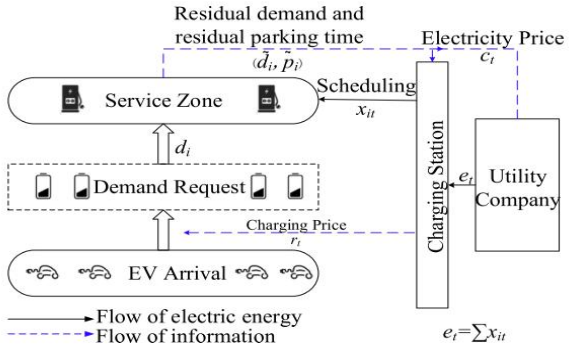
◆ **存在问题：** 约束条件和观测模式与光学望远镜阵不同；难以适用于大规模巡天；自动化调度难以满足

1）无人机任务调度问题



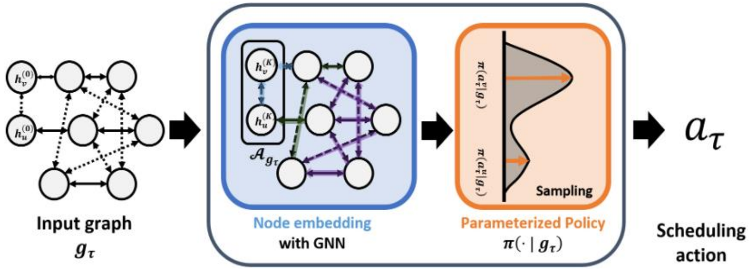
—“Multi-Agent Deep Reinforcement Learning for Task Offloading in UAV-Assisted Mobile Edge Computing”

2）电动汽车充电站的调度控制问题



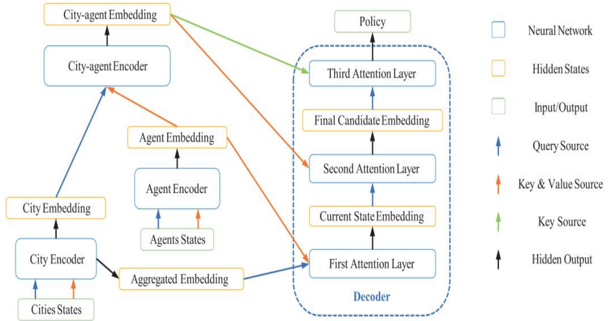
—“Reinforcement Learning for Real-Time Pricing and Scheduling Control in EV Charging Stations”

3）JSSP问题



—“Learning to Schedule Job-shop Problems : Representation and Policy Learning Using Graph Neural Network and Reinforcement Learning”

4）MTSP调度问题

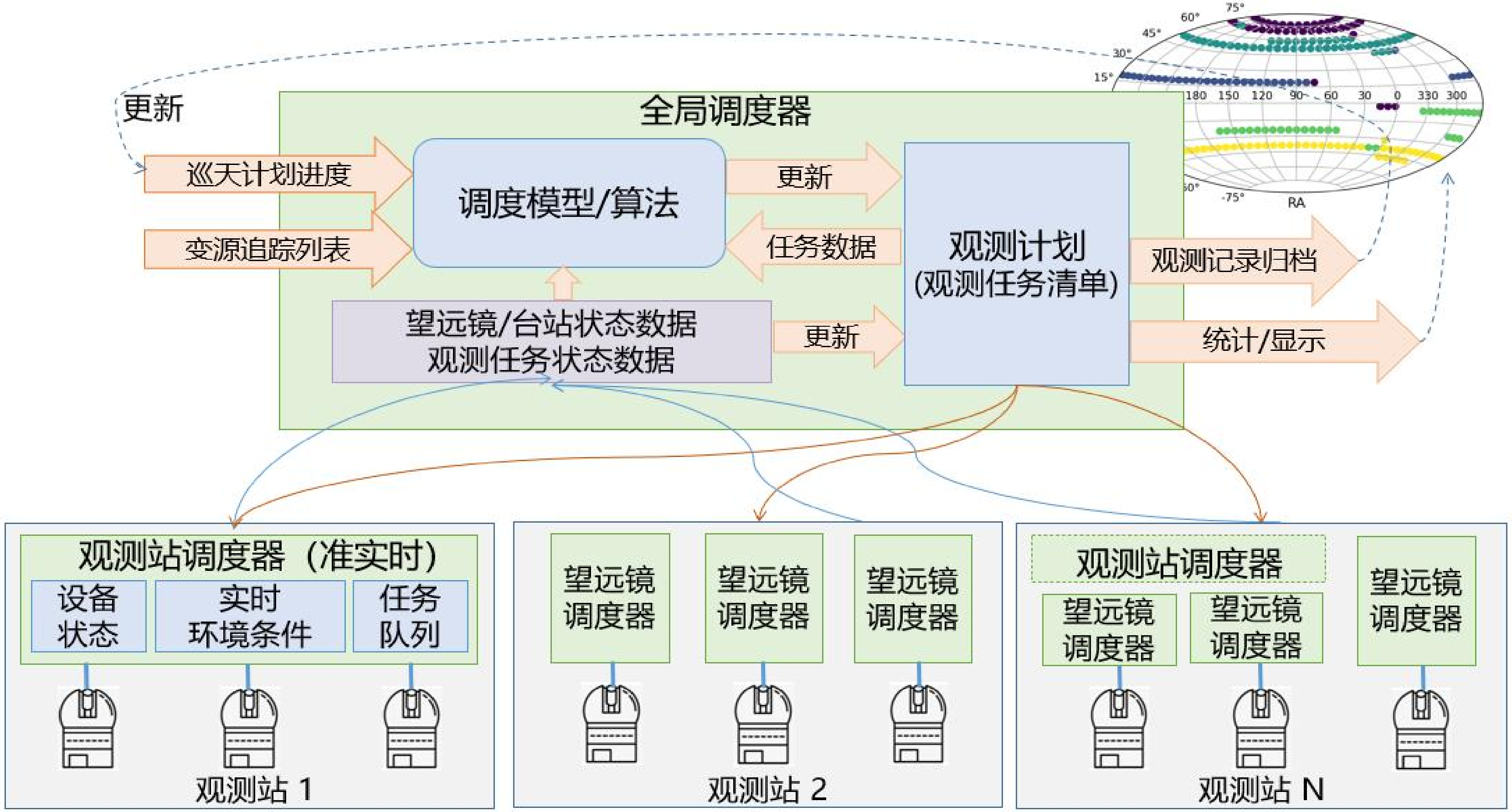


—“ Decentralized Attention-based Neural Network for the MinMax Multiple Traveling Salesman Problem”

- **天文观测调度问题特点：** 空间特性+时间特性；台站呈分布式异构；
需兼容多优化目标和观测模式；对瞬变源的快速响应

面向时域观测的望远镜阵多级观测调度模型

- 提出了**多级观测调度模型**，设计实现了**调度仿真框架**，可支持多种观测模式切换，不同的调度决策算法，动态变化响应等



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环境及数据模拟 ⇨ 约束条件抽象 ⇨ 调度算法 ⇨ 巡天进度可视化

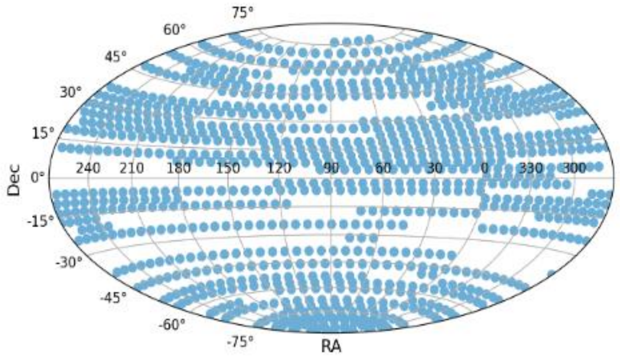
- 研究分布式望远镜阵场景下的主要约束条件和目标，提出**调度性能评定方式**
  - □ **UNO**：观测次数的均匀性。根据调度结果中每个天区的观测次数的标准差来表示。
  - □ **UCOT**：累积曝光时间的均匀性。使用每个天区的总观测时间的标准差表示。
  - □ **UC**：观测间隔（cadence）的均匀性。根据调度结果中每个天区的每次观测开始到前一次观测结束的时间间隔，计算标准差来表示天区之间的均匀性。
  - □ **TAR**：时间分配比率。定义为调度器成功分配的时间占满足观测条件的可观测时间的比例。

- 基于**整数线性规划**，提出了一种**全局调度**求解的算法

Yajie Zhang, Ce Yu, Chao Sun, Zhaohui Shang, Yi Hu, Huiyu Zhi, Jinmao Yang, and Shanjiang Tang. 2023. A Multilevel Scheduling Framework for Distributed Time-domain Large-area Sky Survey Telescope Array. *The Astronomical Journal* 165, 3 , 77.

实验配置

- □ 时间段长度 : 5 mins
- □ 长期调度覆盖时间 : 24 hr
- □ 调度块 (scheduling block) 长度 : 30 mins
- □ 输入观测天区数量 : 50、100、200、500 和 1000
- □ 输入观测台站数量 : 1、2、5、10 和 20



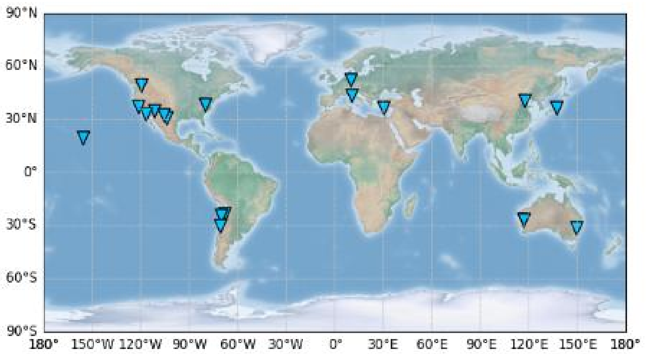


Table 1
Summary of Observation Site Information Used in the Experiments to Simulate the Composition of the Telescope Array

Site	R.A. (deg)	decl. (deg)	Altitude (m)
Subaru	−155.48	19.83	4139.00
TUG	30.34	36.82	2500.00
KAGRA	137.31	36.41	414.18
ALMA	−67.76	−23.03	5000.00
MWA	116.67	−26.70	377.83
Cerro Tololo	−70.82	−30.17	2215.00
VIRGO	10.50	43.63	51.88
DRAO	−119.62	49.32	546.57
G1	9.81	52.25	114.43
CHIME	−119.62	49.32	555.37
Sunspot	−105.82	32.79	2800.00
Hale Telescope	−116.86	33.36	1706.00
Lick Observatory	−121.64	37.34	1290.00
Discovery Channel Telescope	−111.42	34.74	2337.00
Murchison Wide-field Array	116.67	−26.70	377.83
Green Bank Telescope	−79.84	38.43	807.00
Beijing Xing Long Observatory	117.58	40.39	950.00
Anglo-Australian Observatory	149.07	−31.28	1164.00
McDonald Observatory	−104.02	30.67	2075.00
Paranal Observatory	−70.40	−24.63	2669.00

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➢ 调度均匀性

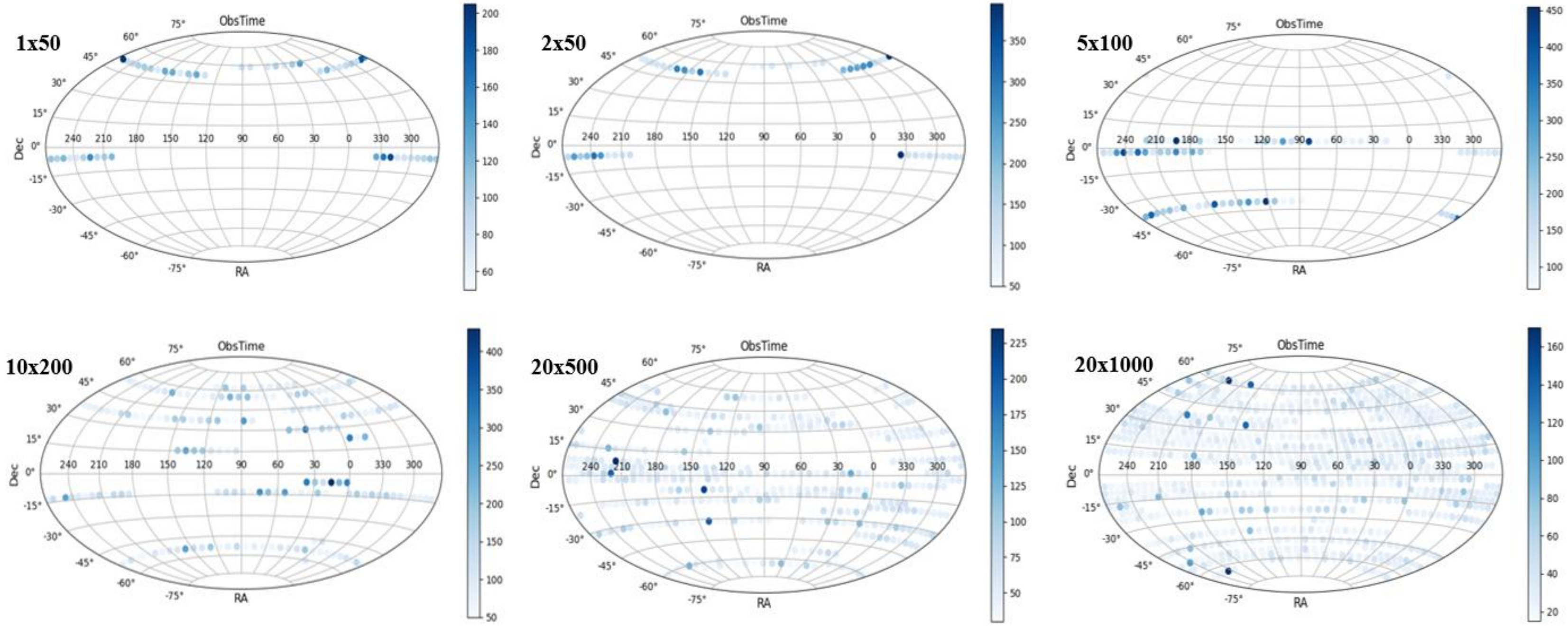
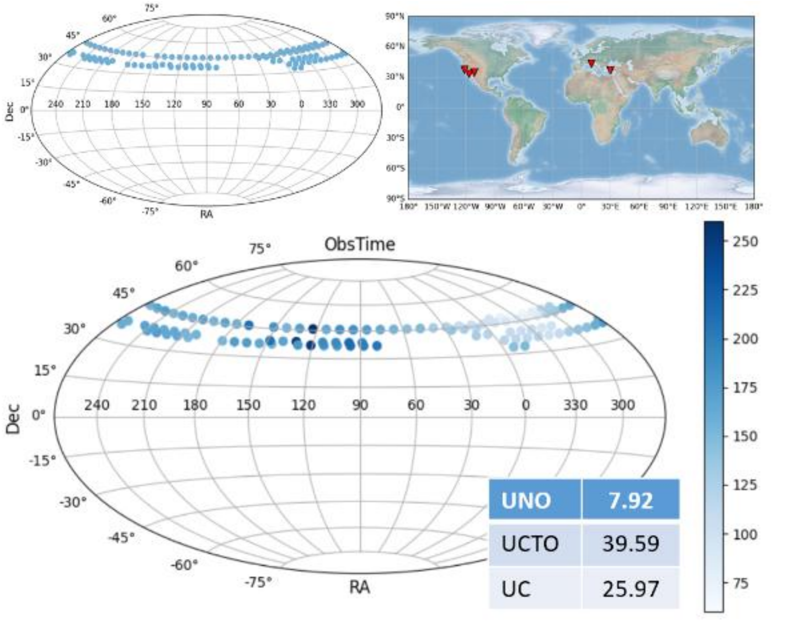


Figure 6. Coverage of cumulative observation time (in minutes) for various datasets after the duration of 10 long-term scheduling processes (10 days). According to the objectives of large-scale time-domain survey missions, the scheduler needs to provide a uniform coverage of the visible sky within each field. It can be seen that, with the expansion of the scale of the sky survey, the uniformity performance will be better.



UNO	7.92
UCTO	39.59
UC	25.97

Figure 7. Observation uniformity evaluations over a time span of one year. The first row represents the locations of the input five sites and 100 fields. The second row shows the results of coverage of cumulative observation time (in minutes) and the uniformity metrics. The annual uniformity of observations shows a stable behavior.

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- **可扩展性**

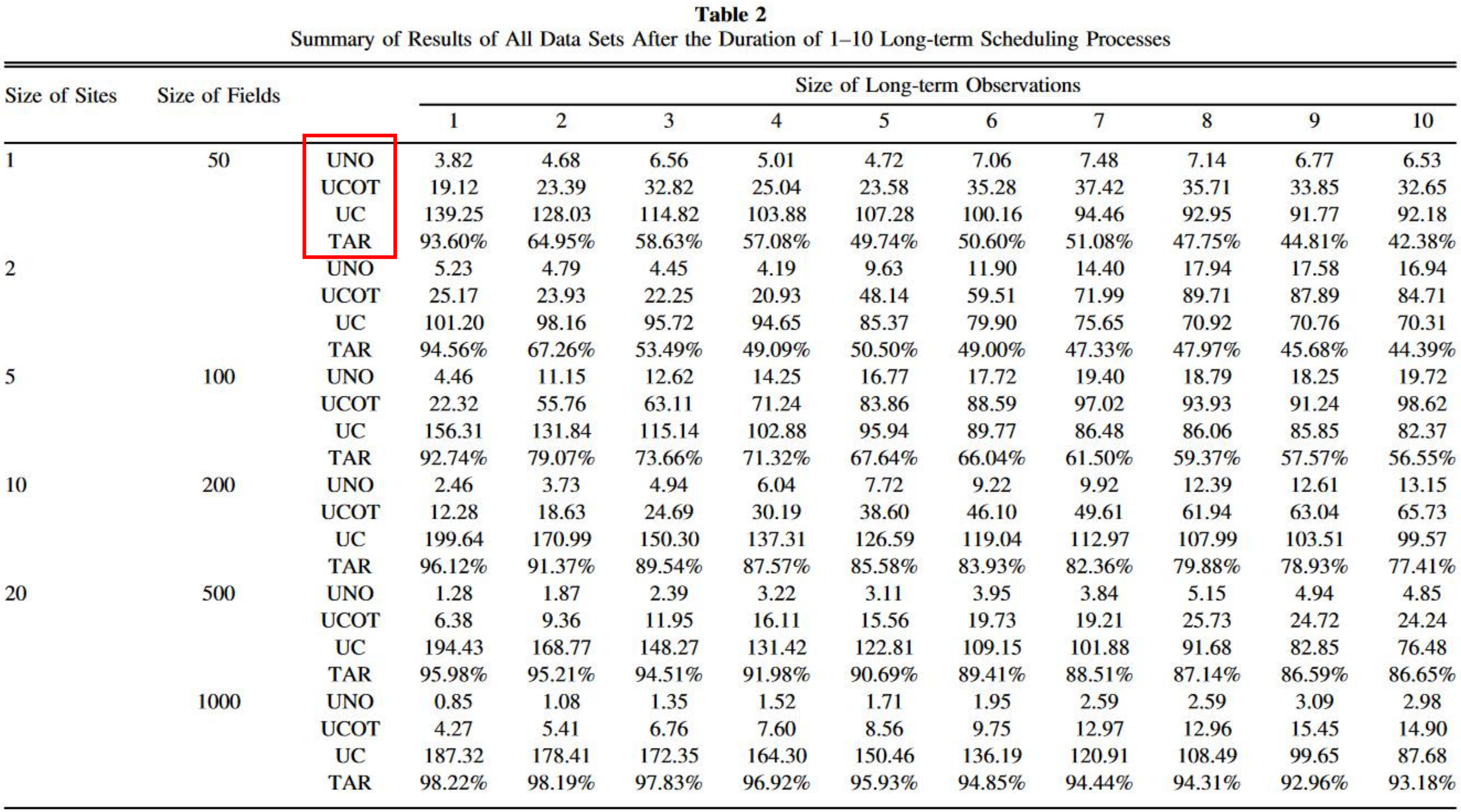

Table 2
Summary of Results of All Data Sets After the Duration of 1–10 Long-term Scheduling Processes

Size of Sites	Size of Fields		Size of Long-term Observations									
			1	2	3	4	5	6	7	8	9	10
1	50	UNO	3.82	4.68	6.56	5.01	4.72	7.06	7.48	7.14	6.77	6.53
		UCOT	19.12	23.39	32.82	25.04	23.58	35.28	37.42	35.71	33.85	32.65
		UC	139.25	128.03	114.82	103.88	107.28	100.16	94.46	92.95	91.77	92.18
		TAR	93.60%	64.95%	58.63%	57.08%	49.74%	50.60%	51.08%	47.75%	44.81%	42.38%
2		UNO	5.23	4.79	4.45	4.19	9.63	11.90	14.40	17.94	17.58	16.94
		UCOT	25.17	23.93	22.25	20.93	48.14	59.51	71.99	89.71	87.89	84.71
		UC	101.20	98.16	95.72	94.65	85.37	79.90	75.65	70.92	70.76	70.31
		TAR	94.56%	67.26%	53.49%	49.09%	50.50%	49.00%	47.33%	47.97%	45.68%	44.39%
5	100	UNO	4.46	11.15	12.62	14.25	16.77	17.72	19.40	18.79	18.25	19.72
		UCOT	22.32	55.76	63.11	71.24	83.86	88.59	97.02	93.93	91.24	98.62
		UC	156.31	131.84	115.14	102.88	95.94	89.77	86.48	86.06	85.85	82.37
		TAR	92.74%	79.07%	73.66%	71.32%	67.64%	66.04%	61.50%	59.37%	57.57%	56.55%
10	200	UNO	2.46	3.73	4.94	6.04	7.72	9.22	9.92	12.39	12.61	13.15
		UCOT	12.28	18.63	24.69	30.19	38.60	46.10	49.61	61.94	63.04	65.73
		UC	199.64	170.99	150.30	137.31	126.59	119.04	112.97	107.99	103.51	99.57
		TAR	96.12%	91.37%	89.54%	87.57%	85.58%	83.93%	82.36%	79.88%	78.93%	77.41%
20	500	UNO	1.28	1.87	2.39	3.22	3.11	3.95	3.84	5.15	4.94	4.85
		UCOT	6.38	9.36	11.95	16.11	15.56	19.73	19.21	25.73	24.72	24.24
		UC	194.43	168.77	148.27	131.42	122.81	109.15	101.88	91.68	82.85	76.48
		TAR	95.98%	95.21%	94.51%	91.98%	90.69%	89.41%	88.51%	87.14%	86.59%	86.65%
	1000	UNO	0.85	1.08	1.35	1.52	1.71	1.95	2.59	2.59	3.09	2.98
		UCOT	4.27	5.41	6.76	7.60	8.56	9.75	12.97	12.96	15.45	14.90
		UC	187.32	178.41	172.35	164.30	150.46	136.19	120.91	108.49	99.65	87.68
		TAR	98.22%	98.19%	97.83%	96.92%	95.93%	94.85%	94.44%	94.31%	92.96%	93.18%

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➢ 观测质量

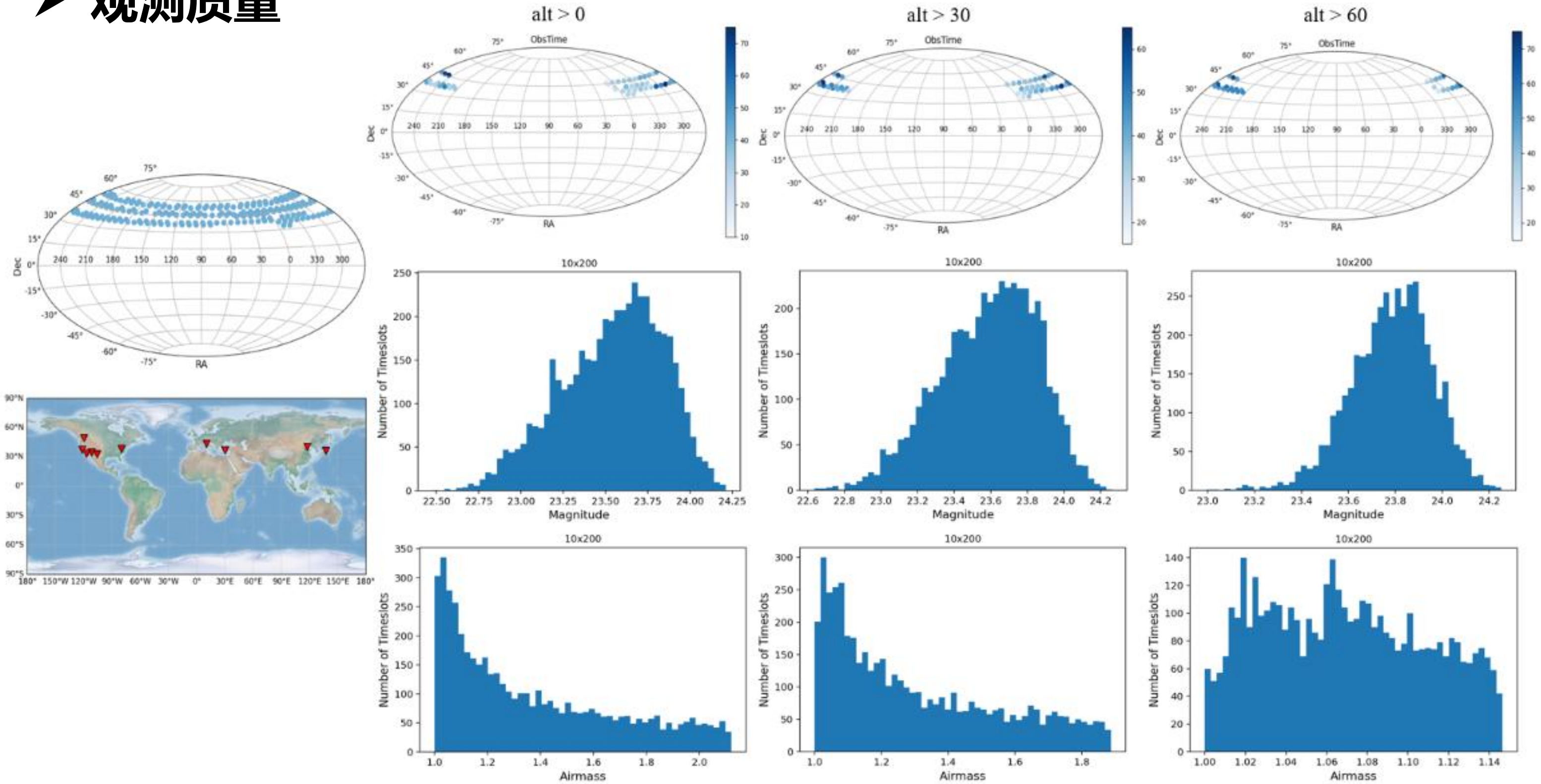

Figure 9. Coverage of cumulative observation time distributions and histograms of 5σ limiting magnitudes of the input 10 sites and 200 fields under various alt constraints after the duration of 10 long-term scheduling processes. The first column shows the locations of input sites and fields. Fields and times with poor observation quality are removed. Moreover, the fields around the zenith will be prioritized.

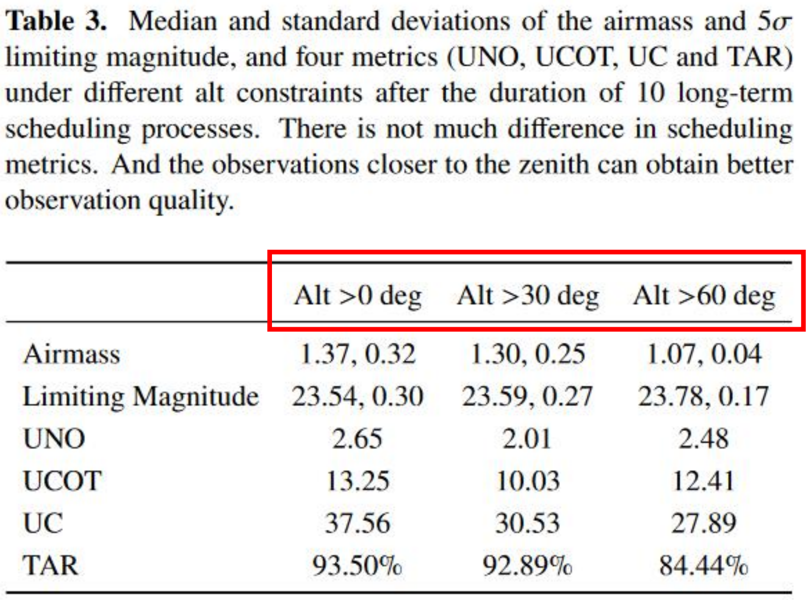

Table 3. Median and standard deviations of the airmass and 5σ limiting magnitude, and four metrics (UNO, UCOT, UC and TAR) under different alt constraints after the duration of 10 long-term scheduling processes. There is not much difference in scheduling metrics. And the observations closer to the zenith can obtain better observation quality.

	Alt >0 deg	Alt >30 deg	Alt >60 deg
Airmass	1.37, 0.32	1.30, 0.25	1.07, 0.04
Limiting Magnitude	23.54, 0.30	23.59, 0.27	23.78, 0.17
UNO	2.65	2.01	2.48
UCOT	13.25	10.03	12.41
UC	37.56	30.53	27.89
TAR	93.50%	92.89%	84.44%

Yajie Zhang, Ce Yu, Chao Sun, Zhaohui Shang, Yi Hu, Huiyu Zhi, Jinmao Yang, and Shanjiang Tang. 2023. A Multilevel Scheduling Framework for Distributed Time-domain Large-area Sky Survey Telescope Array. *The Astronomical Journal* 165, 3 , 77.

03 总结与展望

分布式时域巡天望远镜阵调度

1.分布式望远镜阵观测的特点，分析和归纳调度框架需求

- 能够满足随时间变化的调度约束和优化目标（最优化模型）
- 能够支撑不同规模的观测（分布式架构）
- 减少实际观测中突发情况对巡天的影响（动态调整、仿真）

2.设计多级调度模型和基于线性规划的长周期全局调度策略

3.研发准实时短周期望远镜任务编排算法

4.大规模望远镜时域巡天下的瞬变源追踪算法

Thanks!

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