Adaptive Science Operations in Deep Space Missions Using Offline Belief State Planning

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Problem

Deep space missions require **robust onboard autonomy** to manage environmental uncertainty **without ground intervention**.

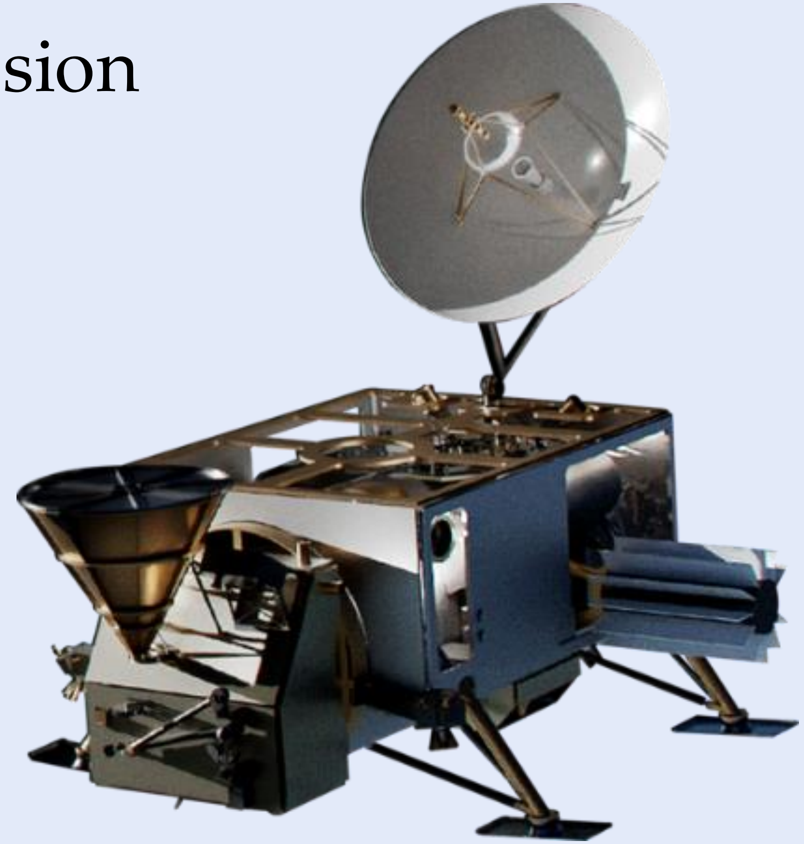
Goal: Design a verifiable autonomy framework that sequences spacecraft science instruments in real time to **maximize science return**.

Case Study: Enceladus Orbilander

NASA and APL flagship astrobiology mission

12-hour communication blackouts,
80-minute delays to Enceladus

Life Detection Suite of **6 instruments**

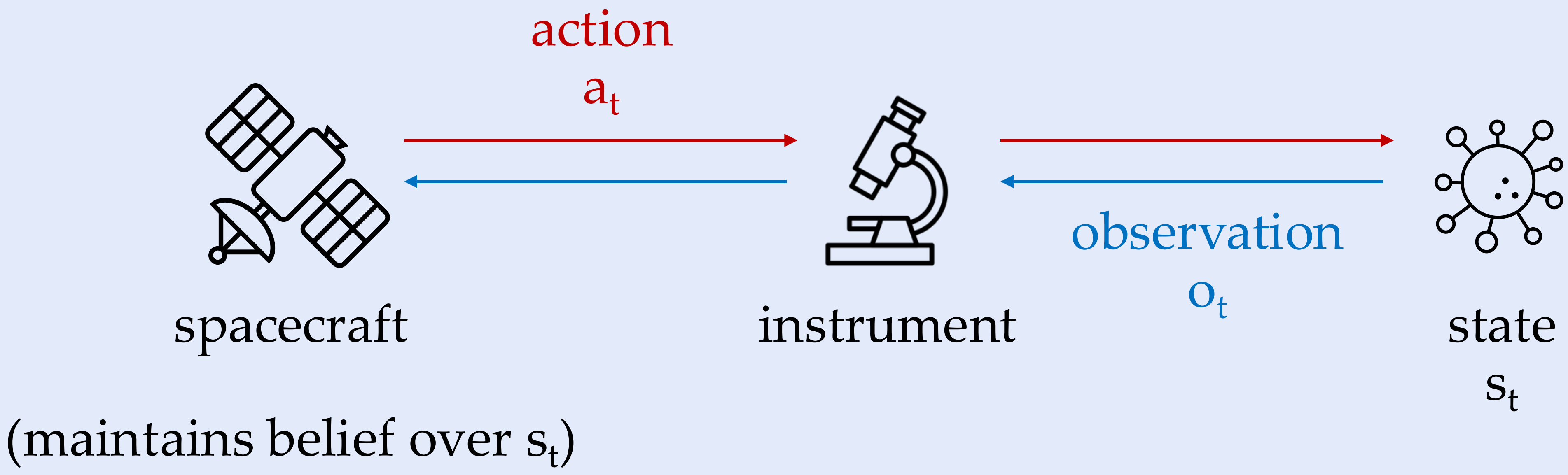


Mackenzie et al. [12]

We present a **partially observable Markov decision process (POMDP)** framework to adaptively sequence science instruments.

We use a **Bayesian network** to model planetary samples and simplify observations.

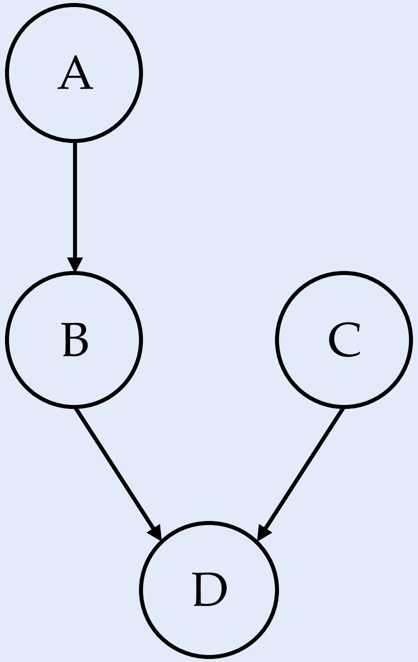
Partially Observable Markov Decision Process (POMDP)



Bayesian Network

B depends on A

$P(B) \neq P(B \mid A)$

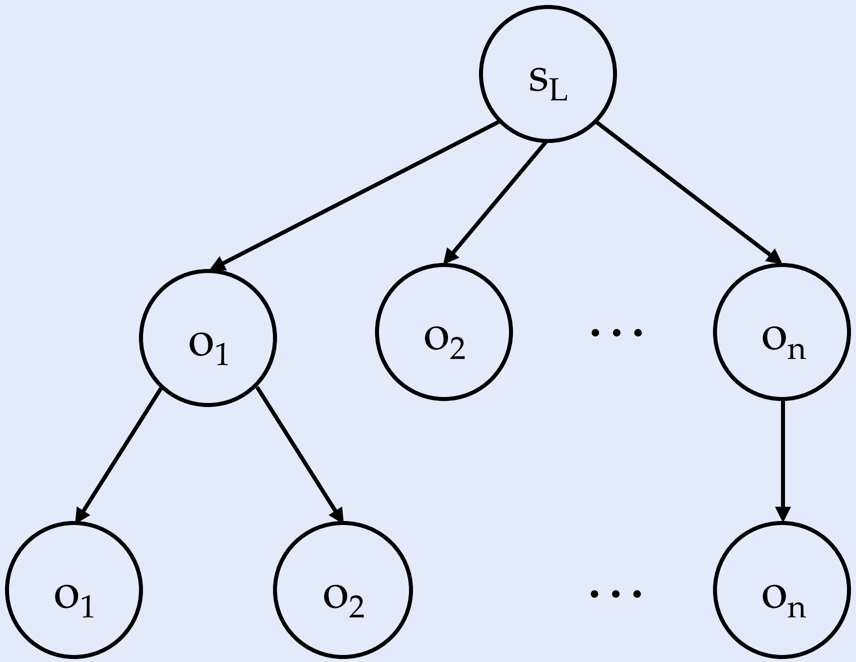


15 → 8 parameters!

Factored Joint PDF:

$$P(A,B,C,D) = P(D|B,C) \cdot P(C) \cdot P(B|A) \cdot P(A)$$

Bayesian Network

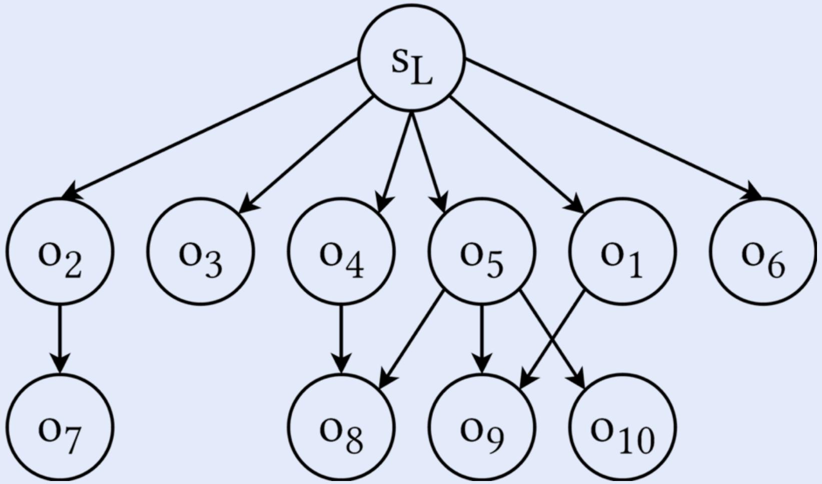


contains life?

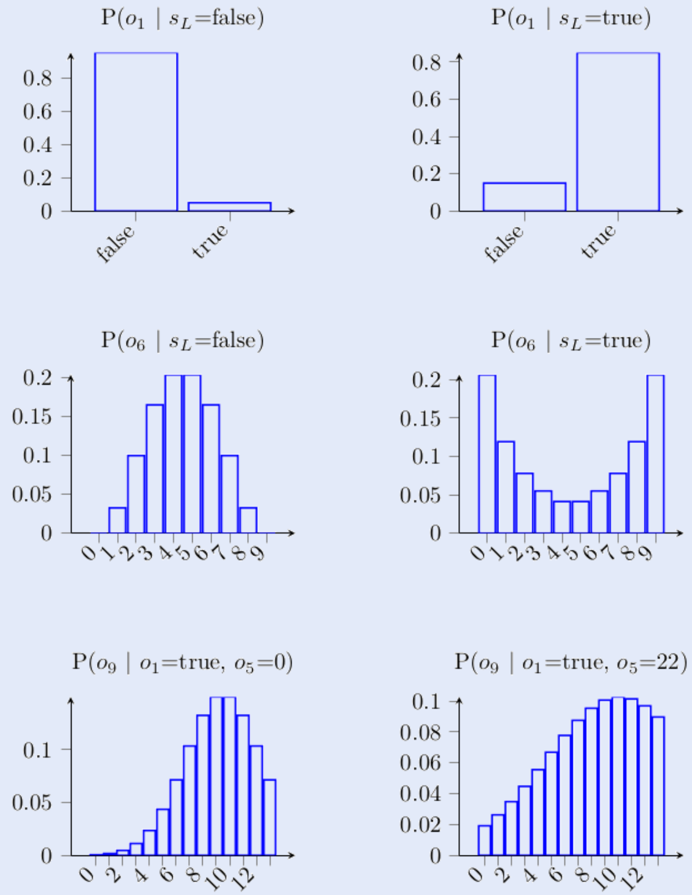
biosignatures
(ex: polyelectrolyte)

habitability metrics
(ex: pH)

Bayesian Network Design



Name	Characteristic	Range	Parent Nodes
s_L	Life	{0,1}	-
o_1	Polyelectrolyte Presence	{0,1}	s_L
o_2	Cell Membrane Presence	{0,1}	s_L
o_3	Autofluorescence	{0,1}	s_L
o_4	Molecular Assembly Index ≥ 15	{0,1}	s_L
o_5	Biotic Amino Acid Diversity	{0, ..., 22}	s_L
o_6	L:R Chirality Ratio (%)	[0, 100]	s_L
o_7	Salinity (%)	[0, 100]	o_2
o_8	CHNOPS Abundance (%)	[0, 100]	o_4, o_5
o_9	pH	[0, 14]	o_1, o_5
o_{10}	Redox Potential [V]	$[-0.5, 0]$	o_5

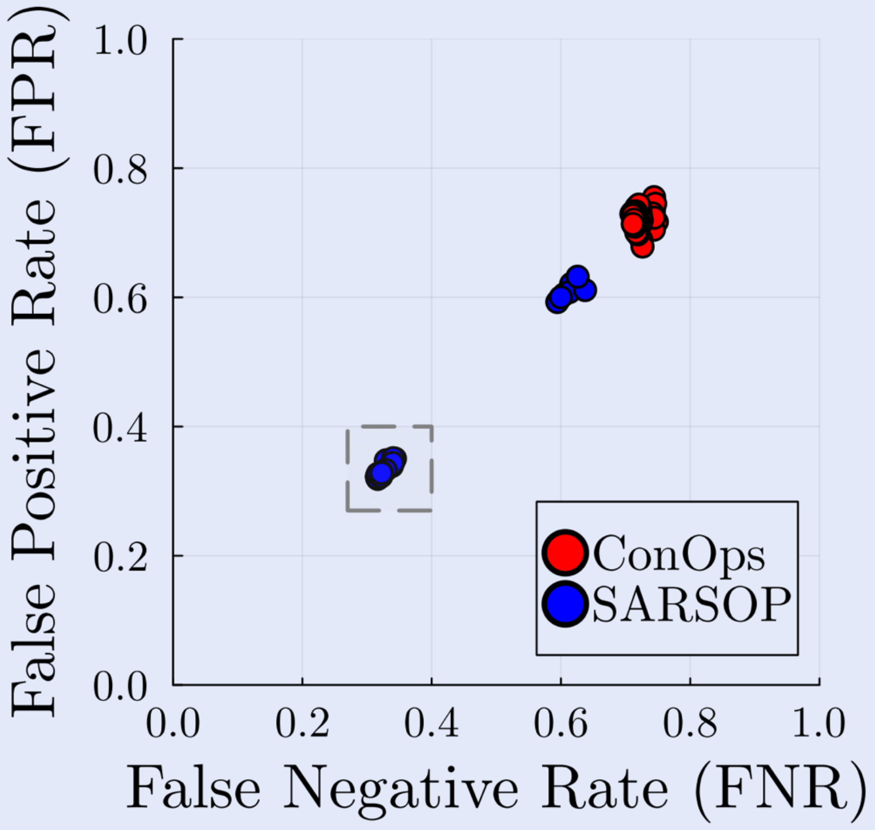


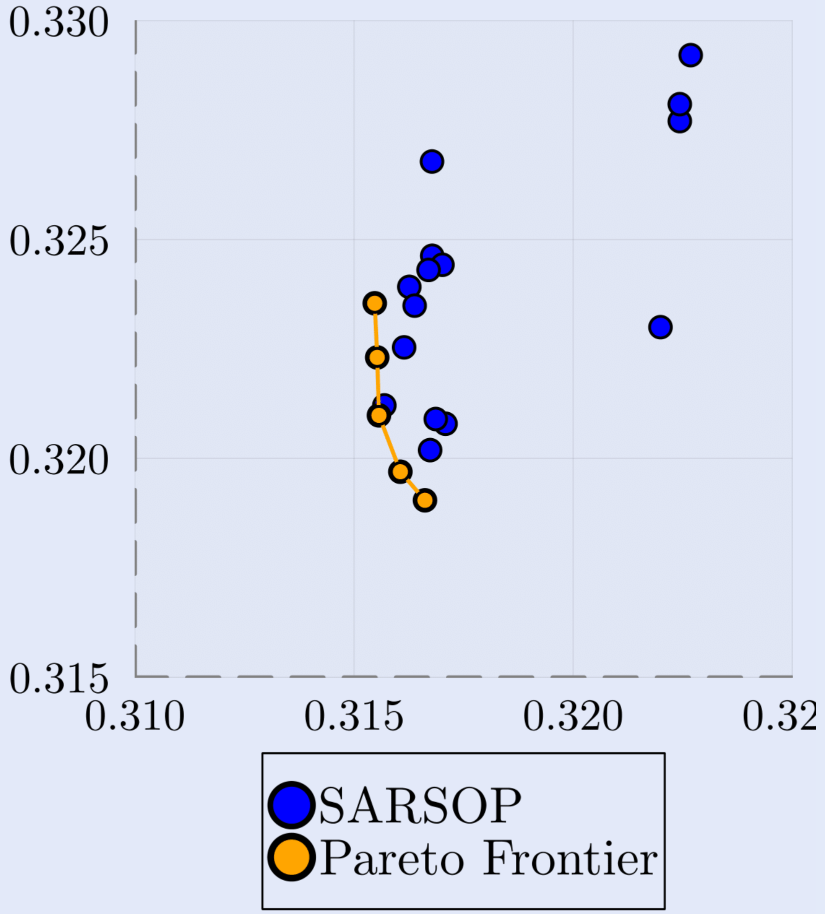
POMDP Design

$$T(s,a) = \begin{cases} s'_L \sim \mathrm{P(life)} \\ s'_V = s_V + \mathcal{N}(v_{\mathrm{acc}}, \sigma^2) & \text{if } a = a_7 \\ s'_L = s_L \\ s'_V = s_V - v_{use}(a) & \text{if } a \in \{a_1, \ldots, a_6\} \\ s' = \text{ terminal} & \text{if } a \in \{a_8, a_9\} \end{cases}$$

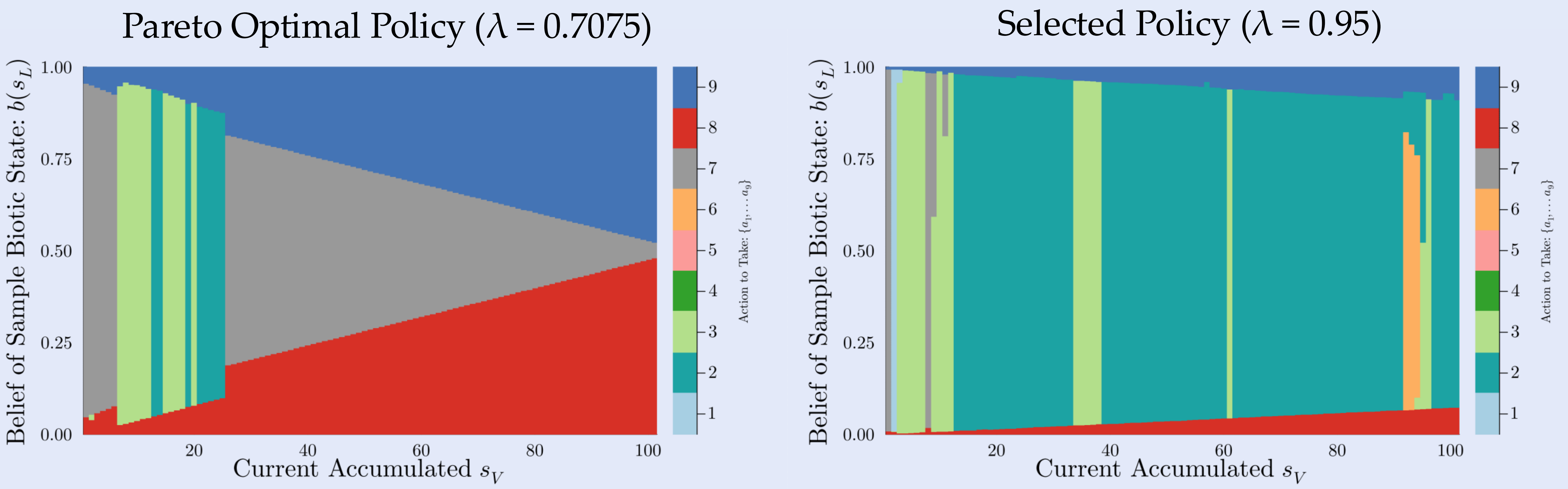
$$R(s,a) = \begin{cases} 0 & \text{Correct declaration} \\ -\lambda & \text{Incorrect declaration} \\ (1-\lambda)\frac{s_V}{s_V^{max}} & \text{Running instrument} \\ -\infty & \text{Infeasible actions} \end{cases}$$

Selecting a Policy





Visualizing Policies



$$\mathcal{A} = \begin{cases} a_1, \ldots, a_6 & \text{Use instrument } a_i \quad \forall i \in \{1, \ldots, 6\} \\ a_7 & \text{Accumulate sample volume} \\ a_8 & \text{Declare abiotic (terminal)} \\ a_9 & \text{Declare biotic (terminal)} \end{cases}$$

Performance

Method	Metric	Sample Accumulation Rate	
		Slow ($v_{acc} = 3\%$)	**Fast** ($v_{acc} = 10\%$)
SARSOP ($\lambda = 0.95$)	FNR (%)	47.7	17.5
	FPR (%)	41.2	17.0
SARSOP ($\lambda = 0.7075$)	FNR (%)	31.4	12.9
	FPR (%)	29.9	18.6
ConOps (Baseline)	FNR (%)	72.4	42.1
	FPR (%)	68.9	43.3

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