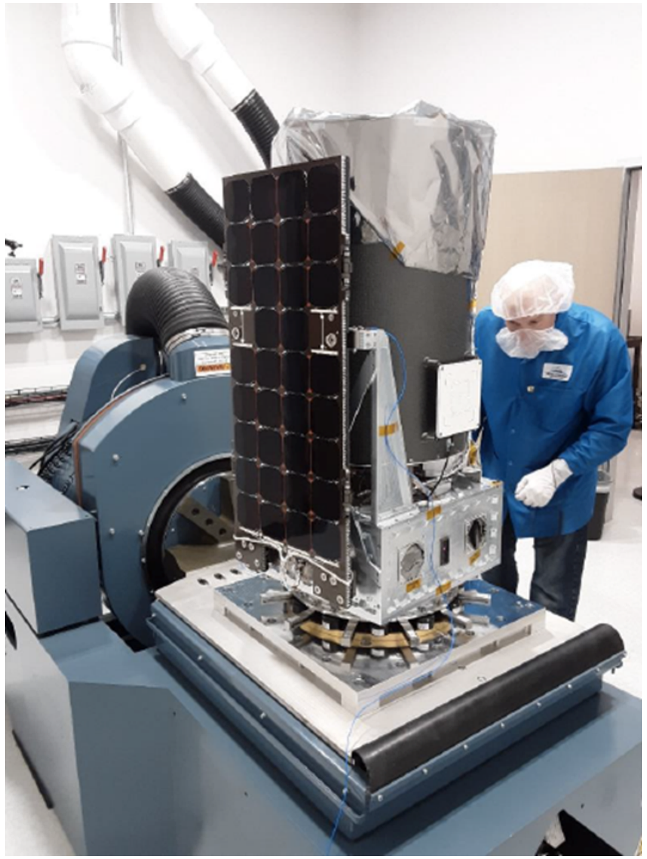
Jet Propulsion Laboratory
California Institute of Technology

MicroArcsecond Small Satellite (MASS) To Discover and Measure Masses of Earth-like Exoplanets

M. Shao



S5 mission ESPA using cubesat parts

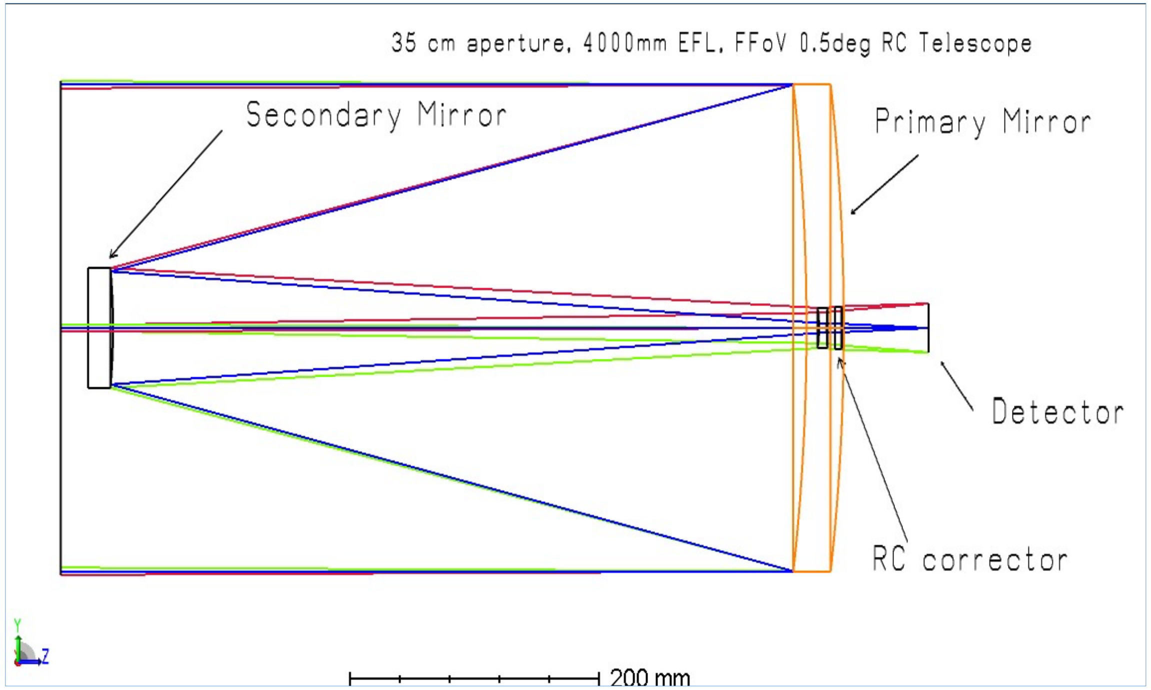
Goal is ~4uas (1 hr) astrometric precision would enable a search for Earth mass planets around ~20 'nearest' FGK stars for ~6 1 Mearth and ~14 2 Mearth mass planets in mid Habitable Zone.

Potential low cost possible taking advantage of low cost mass produced commercial Spacecraft.

HIP	Mass M_E	V mag	Dist., pc	Period, years	Signal, uas	time, hrs	Cumulative, hrs
71683	1	-0.01	1.35	1.21	4.79	100	100
71681	1	1.35	1.35	0.51	3.44	194	295
8102	1	3.49	3.65	0.56	1.32	1,325	1,619
2021	1	2.82	7.47	2.07	1.06	2,043	3,663
3821	1	3.46	5.95	1.10	1.05	2,102	5,765
99240	1	3.55	6.11	1.01	0.99	2,357	8,122
22449	2	3.19	8.03	1.91	0.96	625	8,747
108870	2	4.69	3.63	0.24	0.96	630	9,378
19849	2	4.43	5.04	0.47	0.89	725	10,102
15510	2	4.26	6.06	0.68	0.86	787	10,889
77952	2	2.83	12.31	4.05	0.83	827	11,716
27072	2	3.59	8.97	1.73	0.83	842	12,559
746	2	2.28	16.70	8.06	0.80	899	13,458
96100	2	4.67	5.77	0.49	0.79	913	14,371
57757	2	3.59	10.90	2.16	0.74	1,051	15,422
1599	2	4.23	8.59	1.11	0.73	1,084	16,506
105858	2	4.21	9.22	1.25	0.71	1,141	17,647
64394	2	4.23	9.15	1.19	0.70	1,169	18,816
78072	2	3.85	11.12	1.95	0.70	1,183	19,999
14632	2	4.05	10.53	1.57	0.68	1,250	21,249
12777	2	4.10	11.23	1.70	0.66	1,340	22,589
64924	2	4.74	8.53	0.79	0.64	1,389	23,978

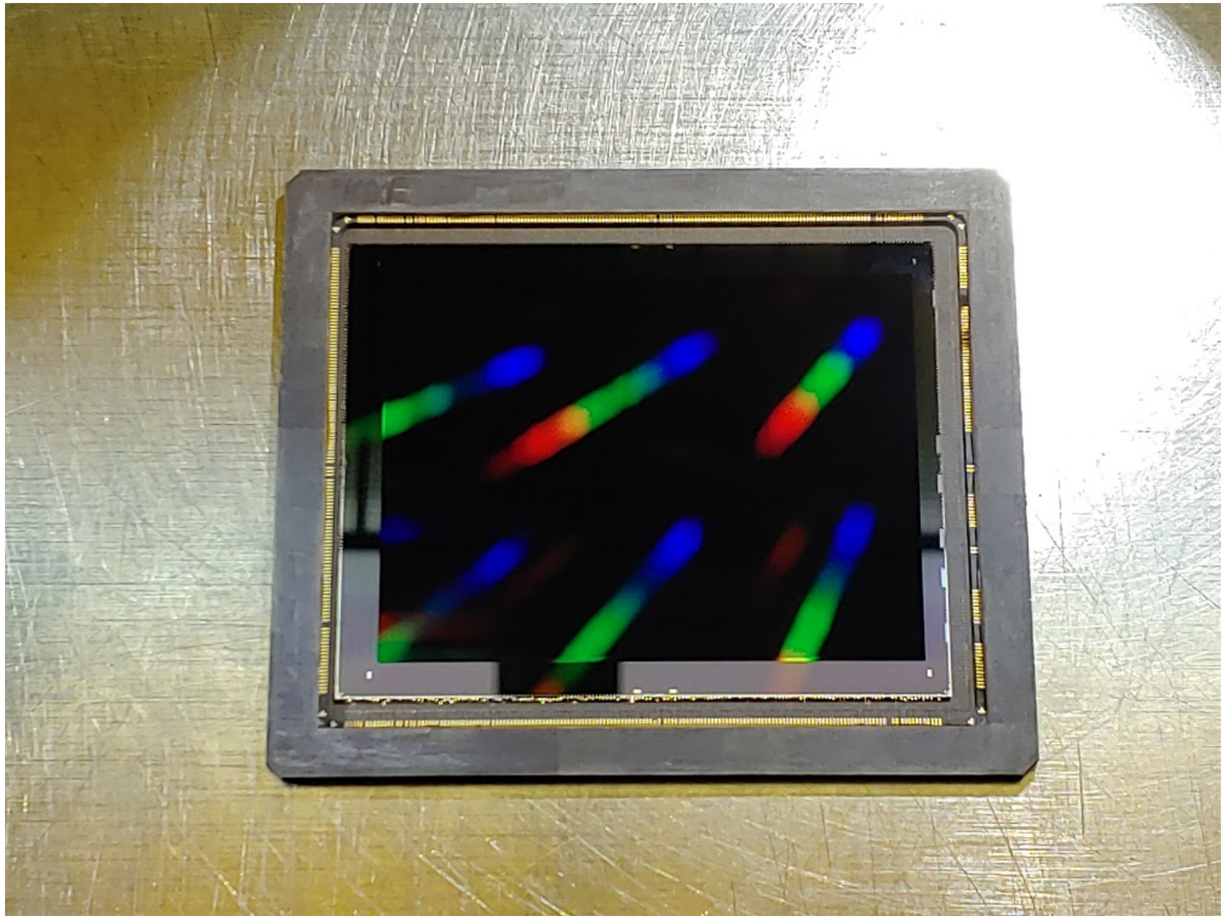
~35cm Telescope >0.5 deg FOV Nyquist sampled Focal Plane

- With next gen sCMOS focal plane
  - Announced Dec 2017
- Sony IMX 411 sensor
- ~150 Mpix
- 3.76um pixels
- Backside
- < 2e read noise
- Commercial ESPA class spacecraft



Large format CMOS sensor

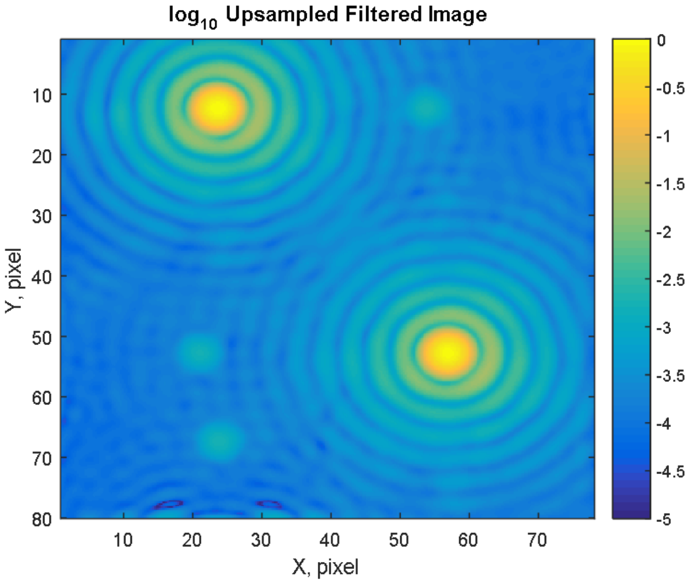
- 150 Mpix (with cover glass removed)
  - 14,208*10,656 pixels
- Backside illuminated
- ~90% peak QE
- 3.76um pix
- 40 Ke full well
- 2 Hz full frame rate
- 1.5e Read noise

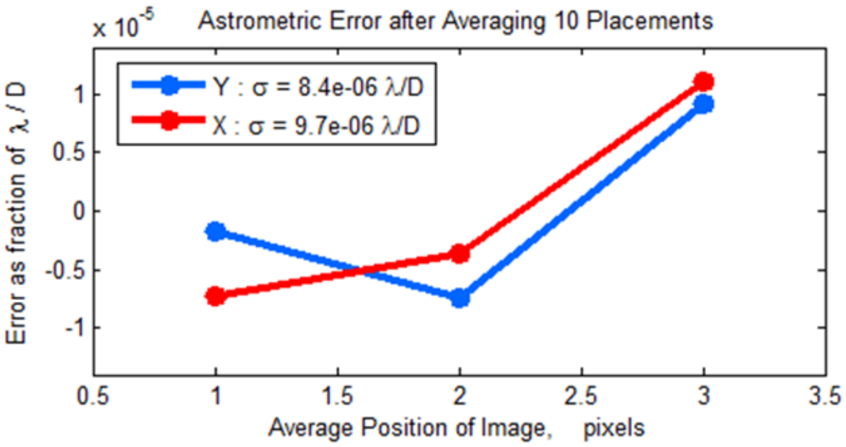


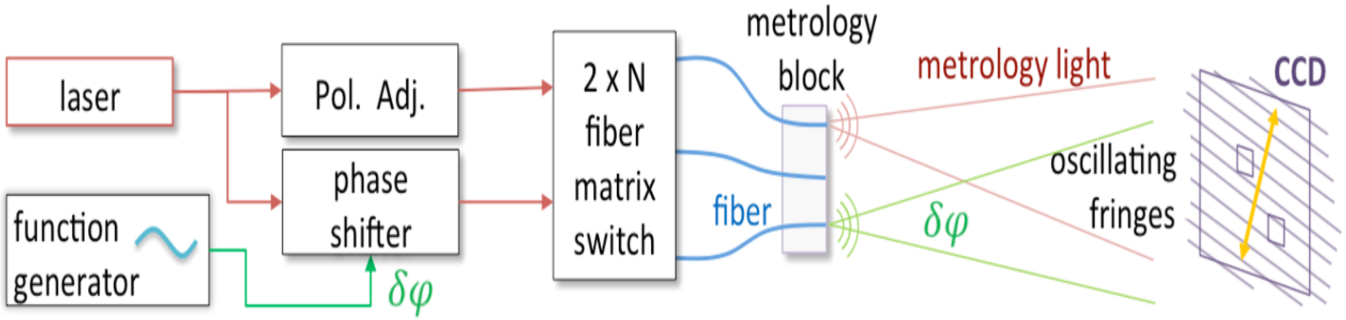
Single digit uas astrometry

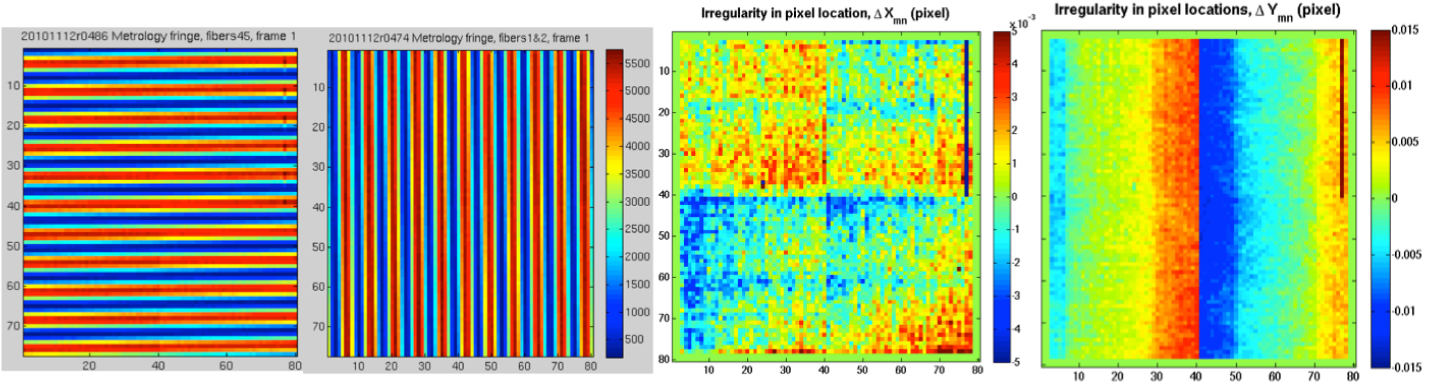
- λ/D for a 35cm telescope ~ 0.35 arcsec 10uas => centroiding to 1 part in 30,000.
- 3 major noise/error sources
  - Photon noise (of ref stars) (Use wide FOV
  - Optical distortion (use crowded field of stars to calibrate – high degree of thermal stability so distortion calibration needed < 1/day)
    - Prefer GEO or HEO altitude
  - Detector imperfections (Use laser fringes to calibrate Pixel positions

SubPixel detector calibration, centroid to $10^{-5}\lambda/D$





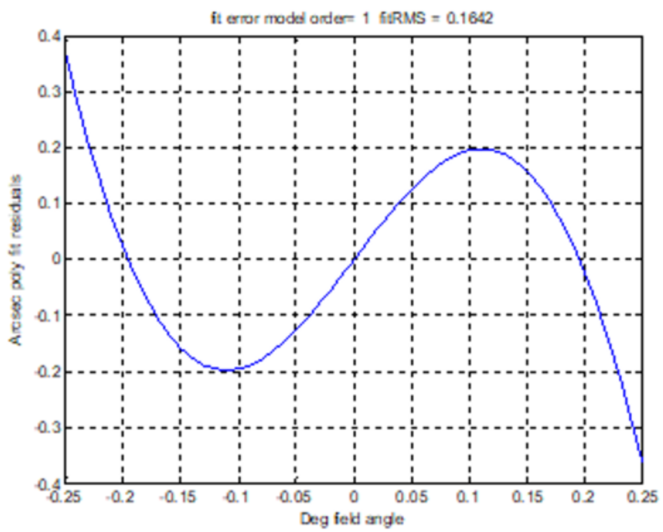


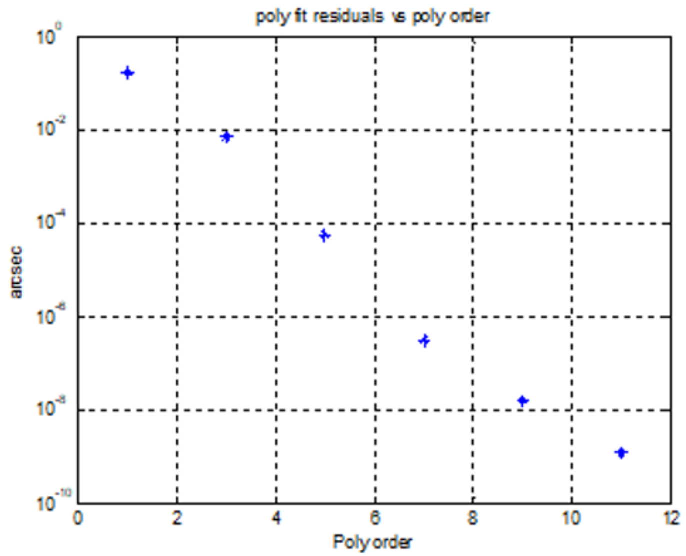


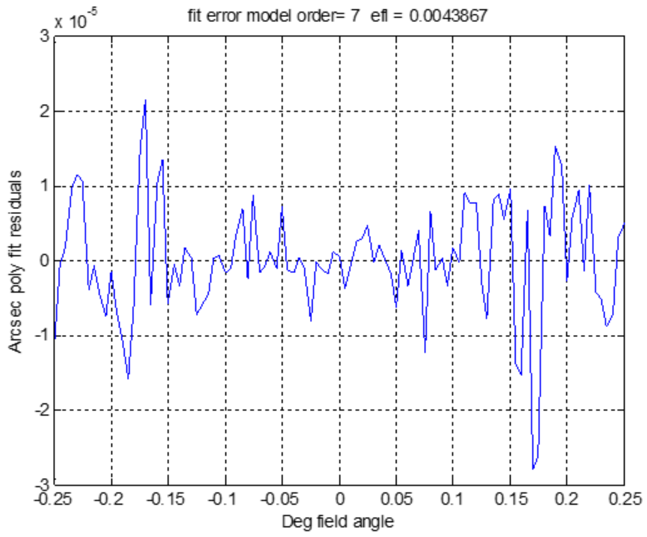
Optics Field Distortion

- Optics field distortion has several sources
  - Perfectly fabricated optics will have distortion. (part of design)
  - Optics are not perfectly manufactured. (l/20 errors 1/f3) to be expected
  - Possible chromatic errors when lenses are used.
- All in modeling, found distortion of the design can be modeled to < 5uas with 9th order poly.

- Also we found that l/20 optical figure errors are also well modeld by the 9th order poly. (optic closes to focal has the most beam walk)
  - Made errors ~2X worse with l/20
- Chromatic errors were dealt with by limiting spectrum to 500~750nm. And designing the system accordingly.
  - What matters is shift in position when star's temperature changes. (offsets don't matter because we're looking for periodic motion)







Astrometric Error Budget

- 4 uas astrometry of a bright target star against 11~16 mag reference stars in 1 hr
  - 100~200 ref stars

Input parameters:			Target star error budget (1 hr):		
Diameter	0.35	m	Target star mag	6	mag
Wavelength	6.50E-07	m	Photon noise	1.23	μas
FOV	31.92	arcmin	Detector geometry	1.74	μas
#pix (λ/D)	2.2		Optics distrotion	1.74	μas
Total pix 1D	11000		Target total noise	2.75	μas
Detector cal	1.00E-04	pixels	**Reference star error budget (1 hr):**		
# dithers	100	per hr	Ref star mag	~11-16	mag
			Avg # of stars	200	
Detect error	1.00E-05	pix/hr	Photon flux	1.36E+06	ph/sec
Detect error	1.74	μas	Ref star flux equiv	8	mag
Field dist error	1.74	μas	Ref photon noise	2.74	μas
			Ref detector noise	0.184	μas
Total QE	0.7		Ref star distort noise	0.184	μas
			Total ref star noise	2.75	μas
Bright. ref star	11	mag			
Faint. ref star	16	mag	**Total diff_astrom. error:**	**3.89**	μas

Thermal Control

- We simulated a thermal control system (for flight) that turned out to be very capable.
- SSO orbit was chosen (no eclipe)
- Examined 1 orbit in SSO (heating by Earth changed)
- Detector stable to < 0.5 mK
- Telescope optics and structure stable to ~ 10mK.
  - SiC structure
- Detector stable to < 5uas (over field)
- Distortion stable to < 5uas (over field)

Spacecraft capabilities needed/Orbit etc

- The focal plane can be read out quickly (compared to CCDs) but because its so large, it does take time. (3 hz). The spacecraft attitude has to be stable to < λ/D on the time scale to read the array. (ideally 0.25~ 0.5 λ/D)
- JPL's Asteria achieved (on a cubesat budget) the type of pointing stability we want.
  - This may require a separate ~6cm telescope with sCMOS focal plane as a fine guidance camera.
- Default SSO orbit. Thermal design to aim for 1 digit mK sensor stability and < 10 mK telescope thermal stability. (SiC telescope thermal stability is slightly better at low Temp (<200K), reducing heater power needed to maintain thermal stabilty.
  - Sufficient battery energy to maintain thermal control during eclipse of S/C in SSO orbit for part of the year.

Commercial Space Industry has dramatically lowered the cost of ESPA class spacecraft.

- Dozens of ESPA class S/C now orbit the earth providing Earth sensing data for Business/Industry. Many of these are “mass produced” in quantities ~10. Mostly they use cubesat parts. (some eg reaction wheels, scaled up for microsats)
  - Mass produced satellites with 30~35cm telescopes and CMOS focal planes can be below $10M/each.
  - One of a kind science missions will be more expensive, but affordable
- Unlike traditional NASA and DoD missions, the spacecraft bus for commercial satellites are bid “fixed price”. Major components such as small (30~35cm telescopes and CCD/CMOS focal planes are also bid fixed price).
  - Reducing the mission cost risk.
- Life time (on their website) advertised as ~5 yrs. (very different from “student cubesat” projects of 10yrs ago)
  - The very low cost of cubesat components, lets one think of redundant components (eg reaction wheels, star trackers, solar panels) to ensure 3~5 yr mission life.
- BUT the cost of these commercial missions are NOT in the NASA/DoD data base. (in some cases historical costs are proprietary, (bid fixed price), NASA Centers and NASA costing may or may not accept these low costs.

Exoplanet Science /Mission Cost

- 6 nearby stars down to 1 Mearth in 1 AU equiv orbit
- ~20 stars down to 2 Mearth in 1 AU equiv orbit

- Team X costing exercise (~3 cost numbers)
- Grass roots (based on ROM quotes)
  - ~ $24M (all costs include 30% reserve)
- 50% cost (based on historical data)
  - ~ $40M
- 70% cost ~ $44M (70% prob mission will be completed within this cost)

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