SOLAR-C Mission
Option-A (Plan-A)

H. Hara（NAOJ)
JAXA SOLAR-C WG

2010 Oct 10

3rd SOLAR-C Science Definition Meeting

Interim Report

Contents

SOLAR-C Concept

- Two options are under study:
  - Option-A (so-called Plan-A):

    Exploration of origin of the solar magnetic activity cycle
    from an out-of-ecliptic orbit
    by X-ray/magnetic field/helioseismic observations

    Toward understanding the solar magnetic activity cycle

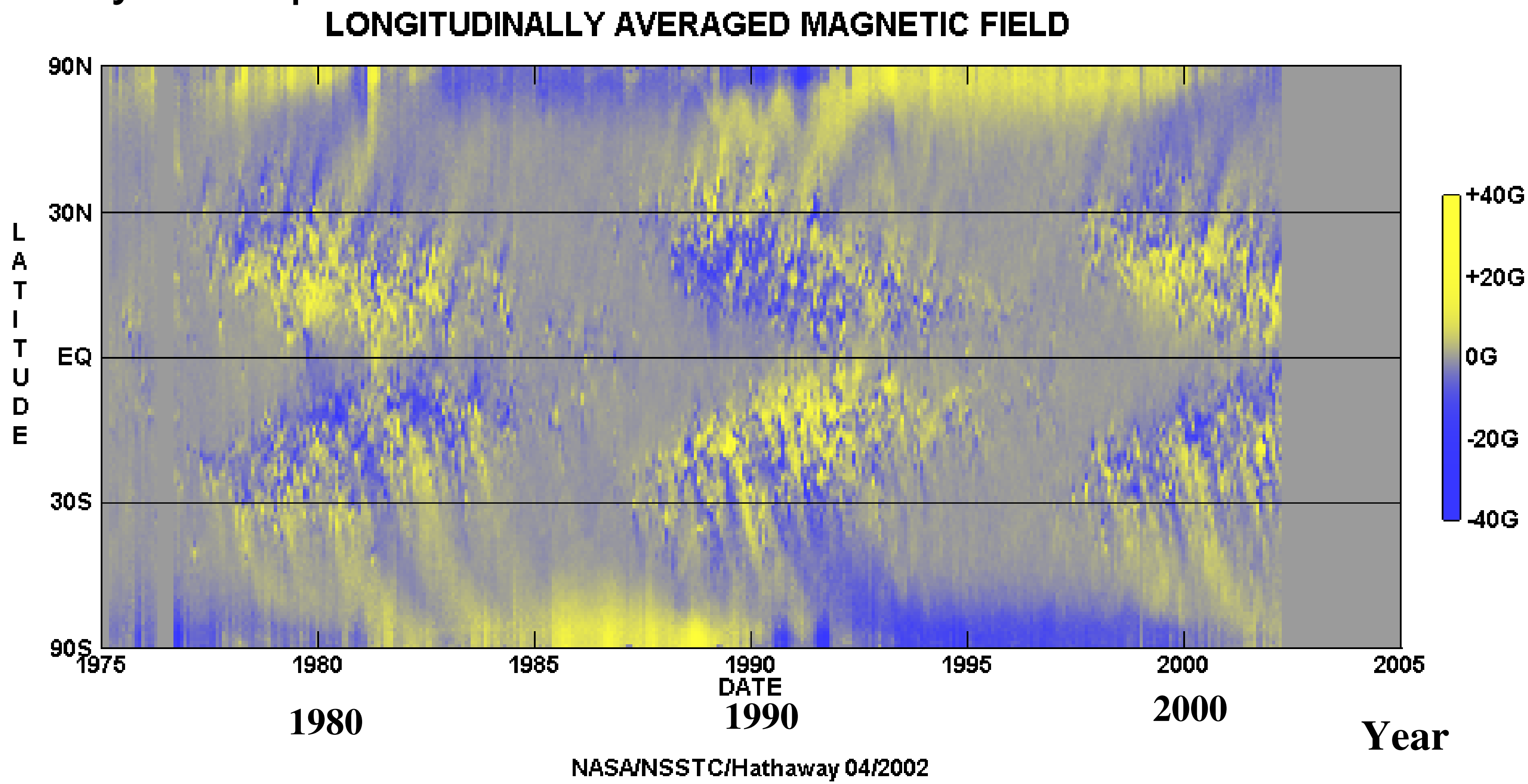
  - Option-B： high-spatial resolution observations of the dynamic Sun with enhanced spectroscopic and polarimetric capabilities

    Toward understanding the magnetic-field dissipation processes

- Launched by JAXA H2A rocket

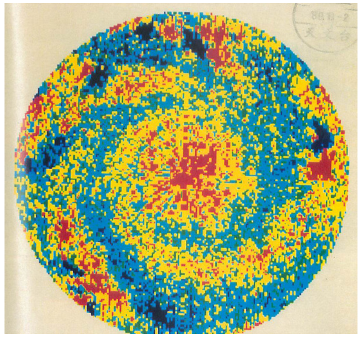
Solar Magnetic Activity Cycle

- How are magnetic fields created in the sun? (Dynamo)
- Internal flows, behavior of polar magnetic fields, and polarity reversal at poles from out-of-ecliptic observations may be important.



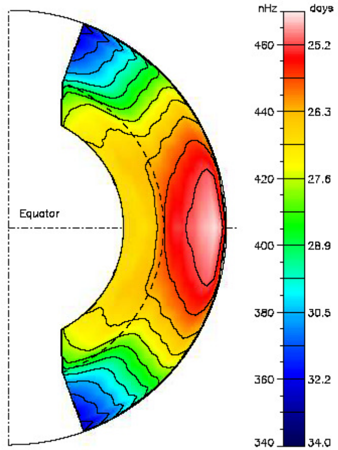
Option-A

Exploration from out-of-ecliptic orbit



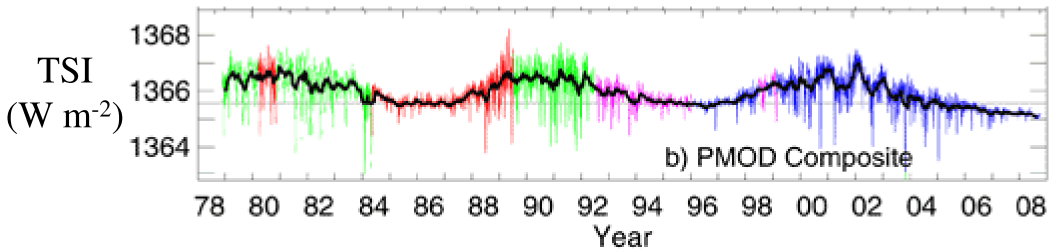
＜Toward understanding the solar dynamo＞

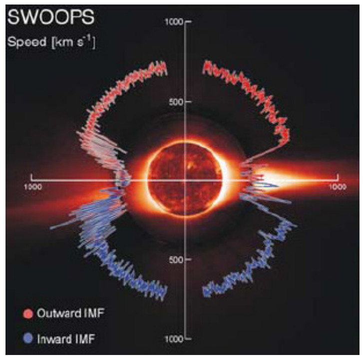
- Surface magnetic activity in polar regions
- Surface/internal flow fields in polar regions
- Convection in polar regions
- Search of tachocline regarded as a source region of strong magnetic fields



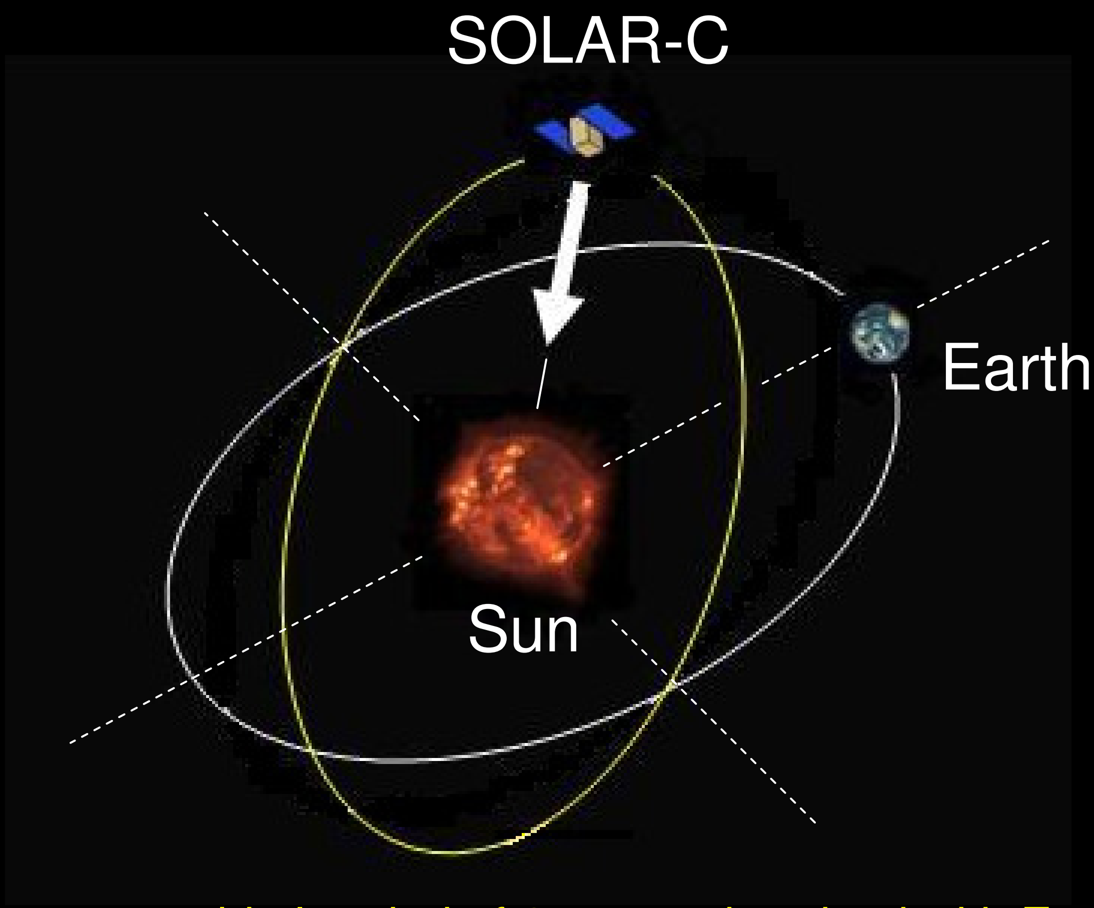
＜Exploration from Vantage Point＞

- Global and local evolution of polar upper atmosphere from new viewpoints
- Total irradiance measurements from out-of-ecliptic orbit
- Solar wind measurement in polar CH and Alfven wave detection from inclined views
- Imaging of CMEs and solar wind/CIR shock structures
- Others





Option-A Target Final Orbit



The target orbital period of 1 yr, synchronized with Earth

Issues on Solar Dynamo from *Interim Report (IR)*

- Q1) What physical processes dominate the generation of global-scale poloidal magnetic fields and where do they operate?
- Q2) How does the transformation between the poloidal (polar) and toroidal (active regions) magnetic fluxes occur? How does this regulate the cyclic magnetic activity?
- Q3) What are the structure and the evolution of the solar differential rotation, and the mean, large-scale meridional flow, how are they maintained and how do they vary with the solar cycle?
- Q4) What is the dynamical origin of photospheric active regions? What is the role of the tachocline?
- Q5) How can we predict sunspot cycles and periods of high solar activity?

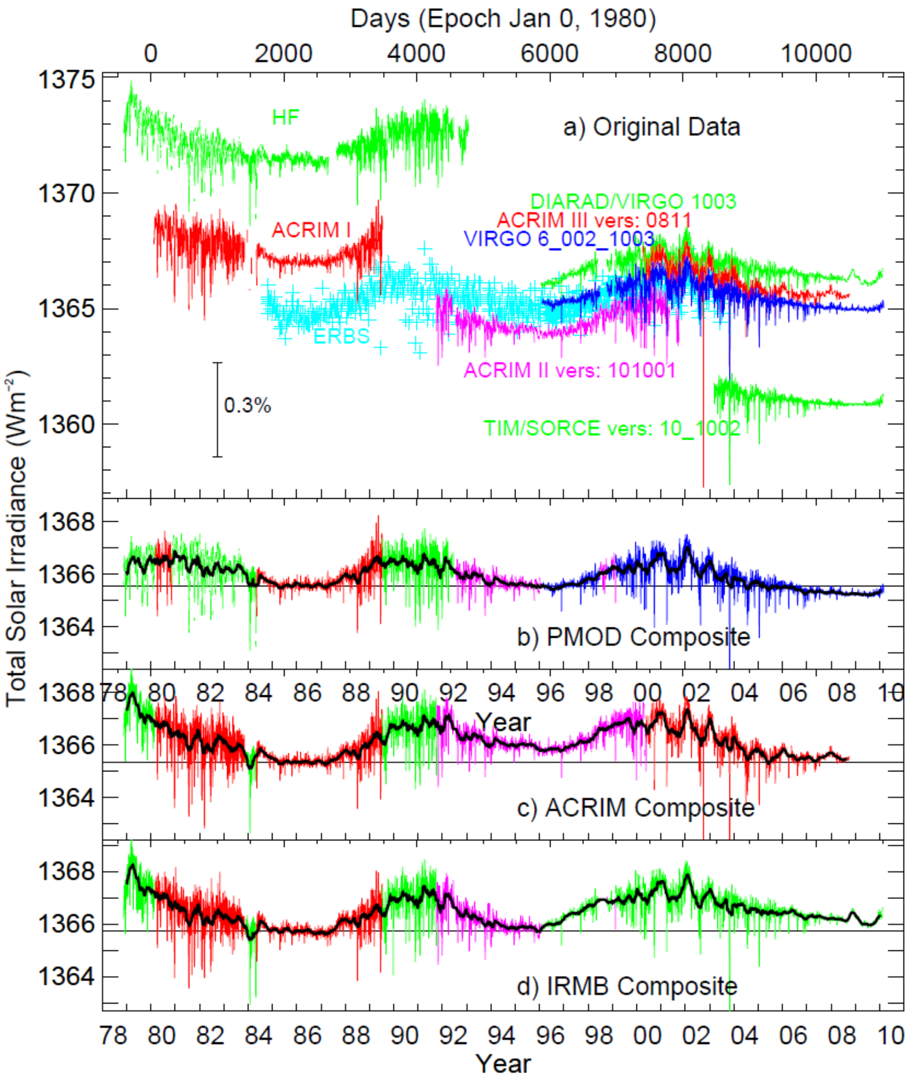
Prime Measurement Targets in S-C for understanding Solar Dynamo

- T1) Differential rotation and meridional flow in the polar regions and the deep convection zone
- T2) Photospheric magnetic flux distribution and evolution in the polar regions
- T3) Dynamical coupling between magnetic fields and flows
- T4) Structure and evolution of solar convection

Obs.of upper solar atmosphere currently described in *IR*

- Formation/evolution of coronal structures
  - Global-scale coronal structure in polar points
  - Plume
  - Small-scale bright points
- Solar wind
  - Spectroscopic detection of Alfven waves by different view angles
  - Restrict the range of $T_{\perp}/T_{//}$ in O v 1032 observations for the inner corona by different view angles
  - No description on the in-situ solar wind measurements on S-C

Total Solar Irradiance (TSI) from out-of-ecliptic plane



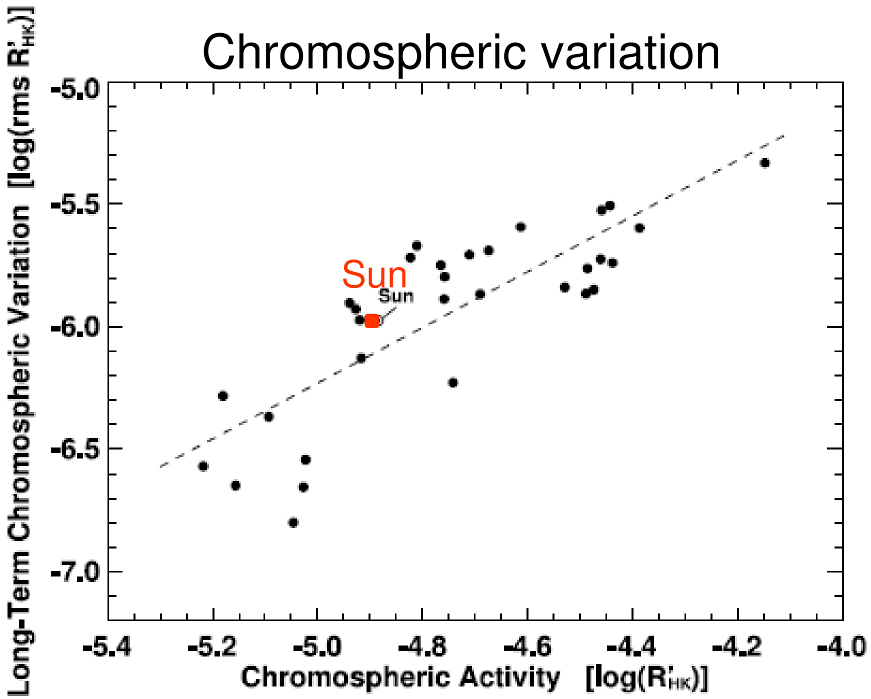
- Understand the sun as a star
- Solar irradiance TSI cycle variation ~0.1% p-p

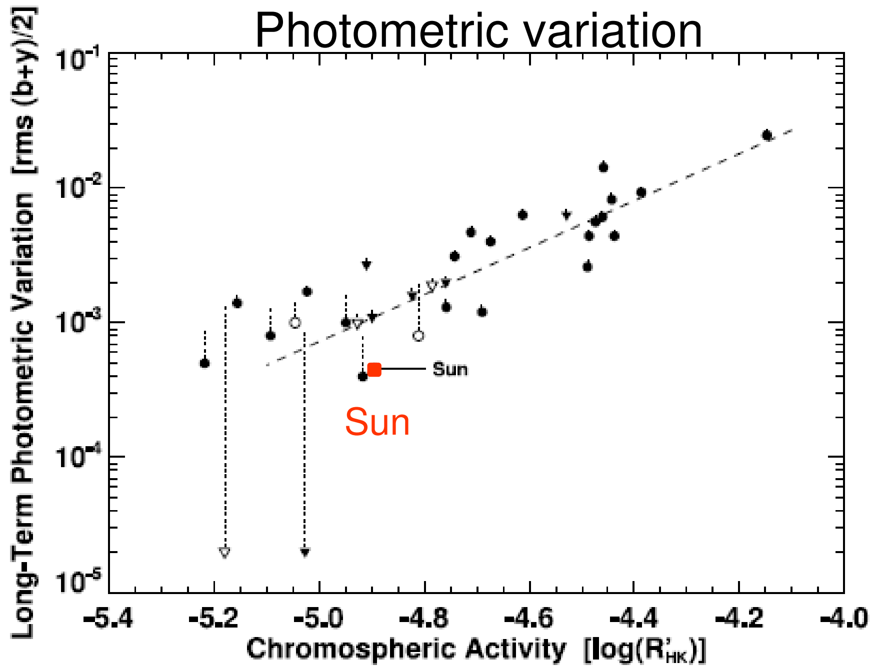
Figure from PMOD WRC homepage

Photometric variation of solar type stars

- Solar type stars show larger amplitude photometric variations, (though the number of sample is small…)
- Is it due to a difference in viewing angle to activity belts?

This will be answered by TSI observations from S-C out-of-ecliptic orbit.

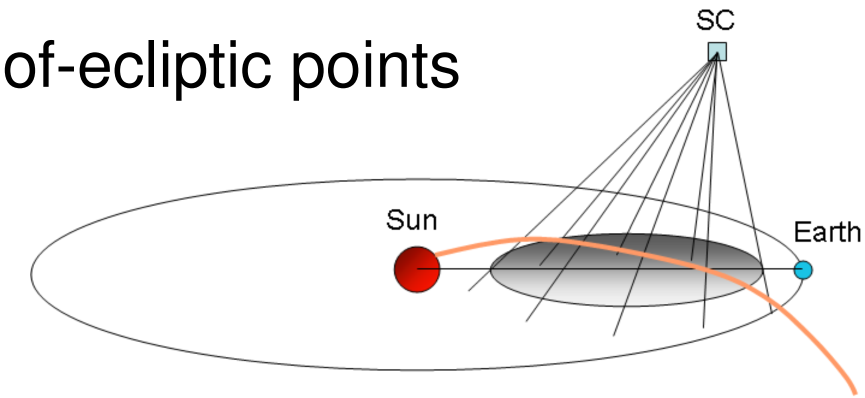




Lockwood et al. 2007, ApJS,171, 260

Optional targets when we can have payload mass

- CME/CIR imaging from out-of-ecliptic points



- Monitoring cosmic rays,

  which relates to generation of cosmogenic isotopes (^{14}C, ^{10}Be, ..), to understand the transport processes in the heliosphere [This is just an idea, need to consider more for justification.] A quick scan of heliosphere in the solar cycle may give a new hint to understand the discrepancy between the model and Ulysses results.

Option-A : Model Payload

Each has a space heritage/a slightly modified version in missions that have been flown.

- Visible-light Magnetic-field and Doppler imager
  - full-disk observations
  - Internal flow structures, mag. fields, convection, .. in polar regions
- X-ray/EUV telescope
  - Coronal dynamics in polar regions, synergy with coronal imagers, observing the sun around the earth, in stereo-scopic views
- EUV imaging spectrometer
  - Flow/wave structures in polar regions (plume, solar wind)
- Total irradiance monitor
  - Latitudinal distribution of surface irradiance

- Others (Options at present)
  - Heliospheric imager: CME imaging, solar wind/CIR shock structures
  - In-situ instruments (CR detector, magnetometer?, etc.; not defined)
- Total mass 130 kg (tentative allocation for design activity)
- Detailed optical layout studies not described in *IR*

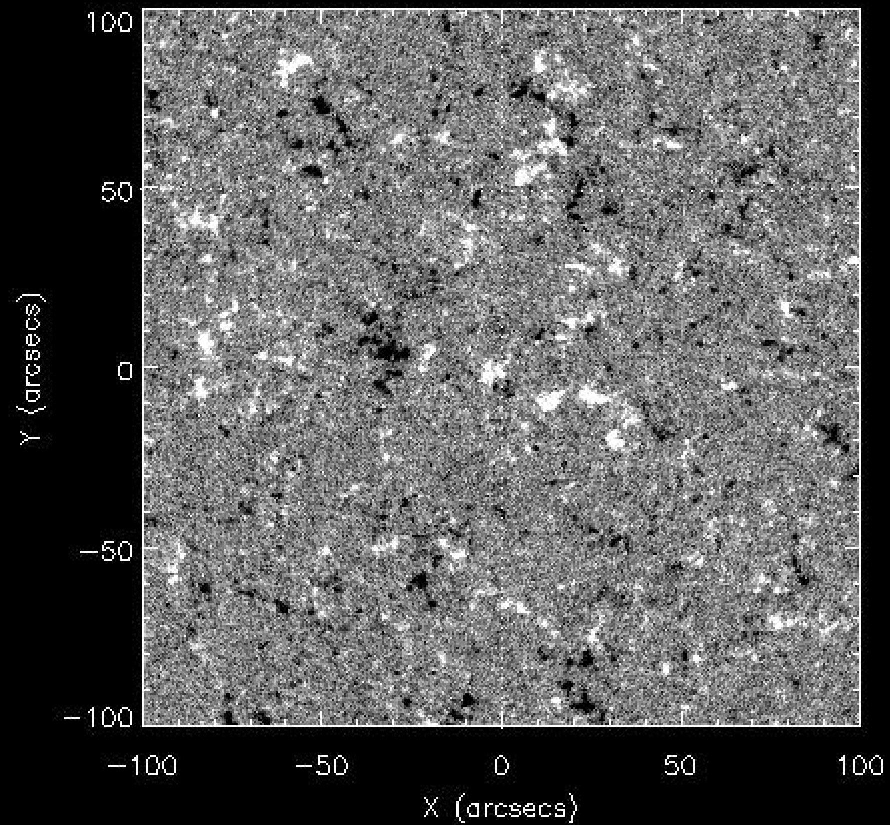
Requirements for S/C System Design

- Duration >40 days (TBD) for a solar latitude of >30 deg (TBD)
  - Target of max. latitude : ~40 deg (higher is better, of course)
  - Need to define these numbers clearly from evaluation through helioseismic model calculations
- Distance to the Sun in the final orbit: 1.0 AU
  - Minimum distance to the sun is 0.7 AU from the thermal-design point of view
  - Maximum distance to the sun is not defined because of a possibility of ballistic orbits by Jupiter swing-by
- Use 7 deg tilt angle of the solar rotation axis to the ecliptic plane

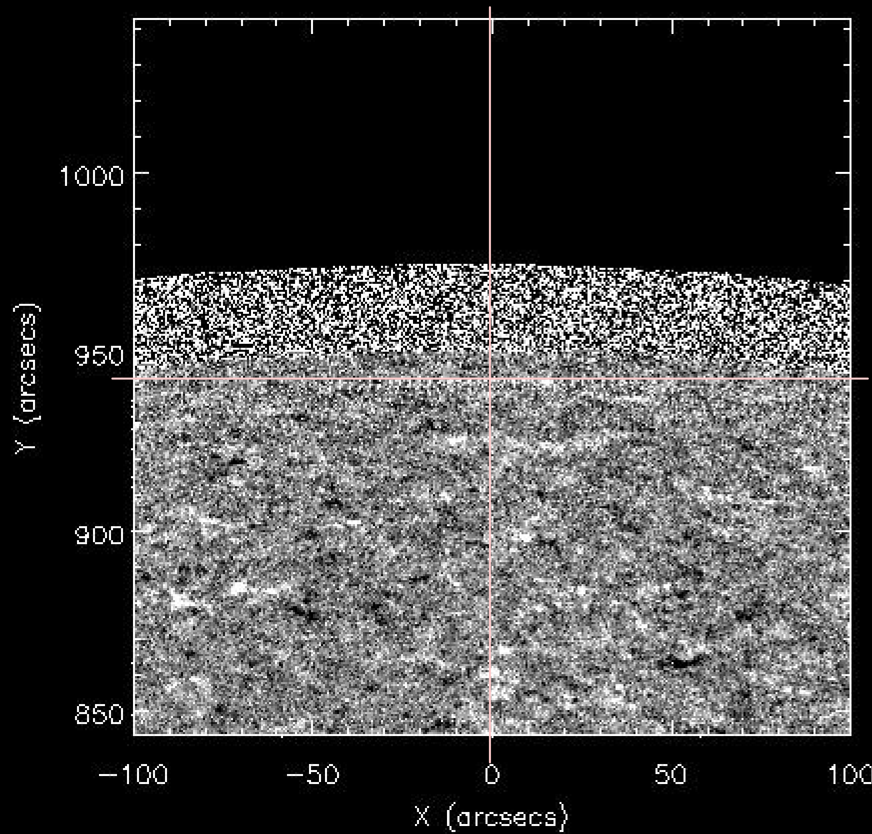
- Duration of cruise phase to the final orbit: ~5 years
  - Need 40-days (TBD) observations near perihelion/aphelion points in the cruise phase
- Payload weight: 130 kg
- Data recording rate: >100 kbps ave.
- Mission life:

  cruise phase N_0~5 yr + N_1 yr + extended duration N_2 yr (total ~N_3 yr)

Disc center

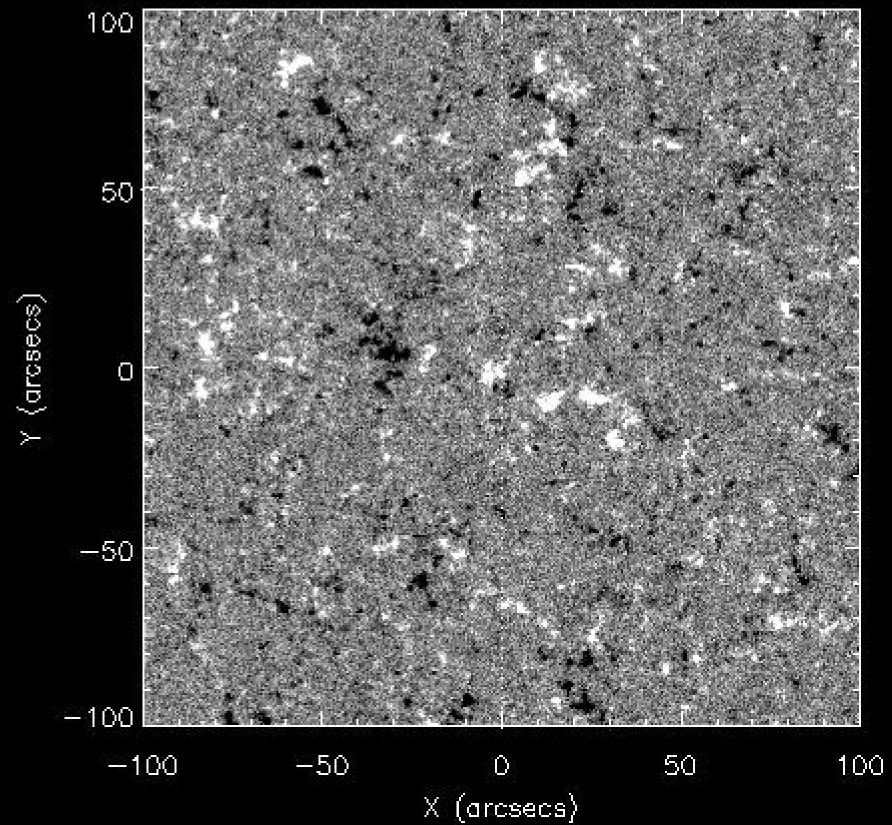


Virtual View of Solar North Pole
at 7 deg from solar equatorial plane

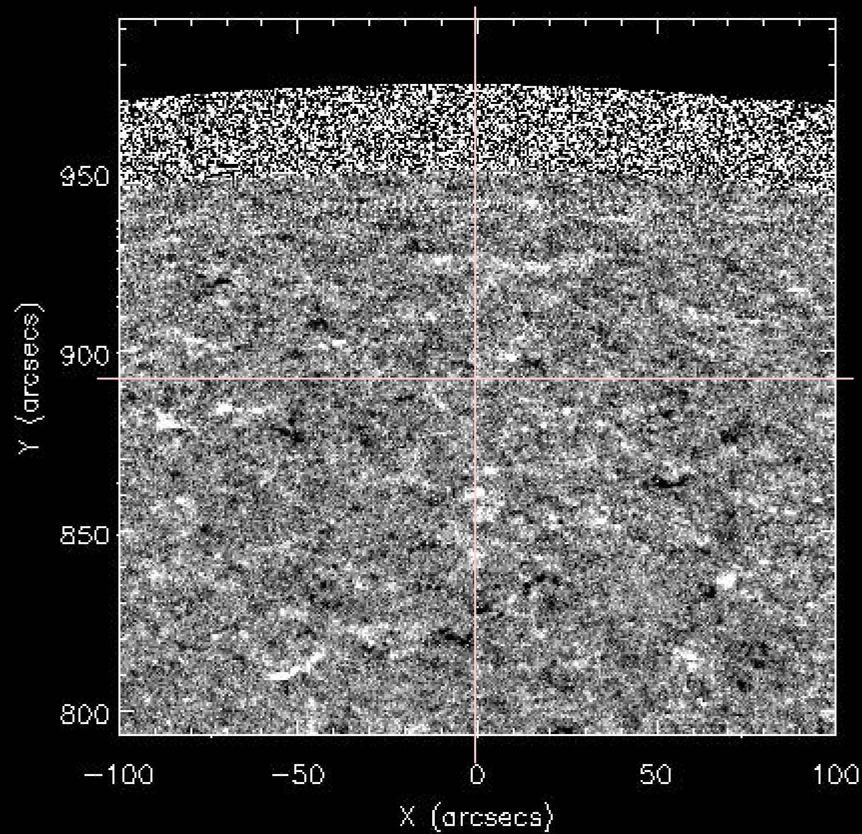


Data from a single FITS data of HMI/SDO 45s-cadence Longitudinal Magnetic Field

Disc center

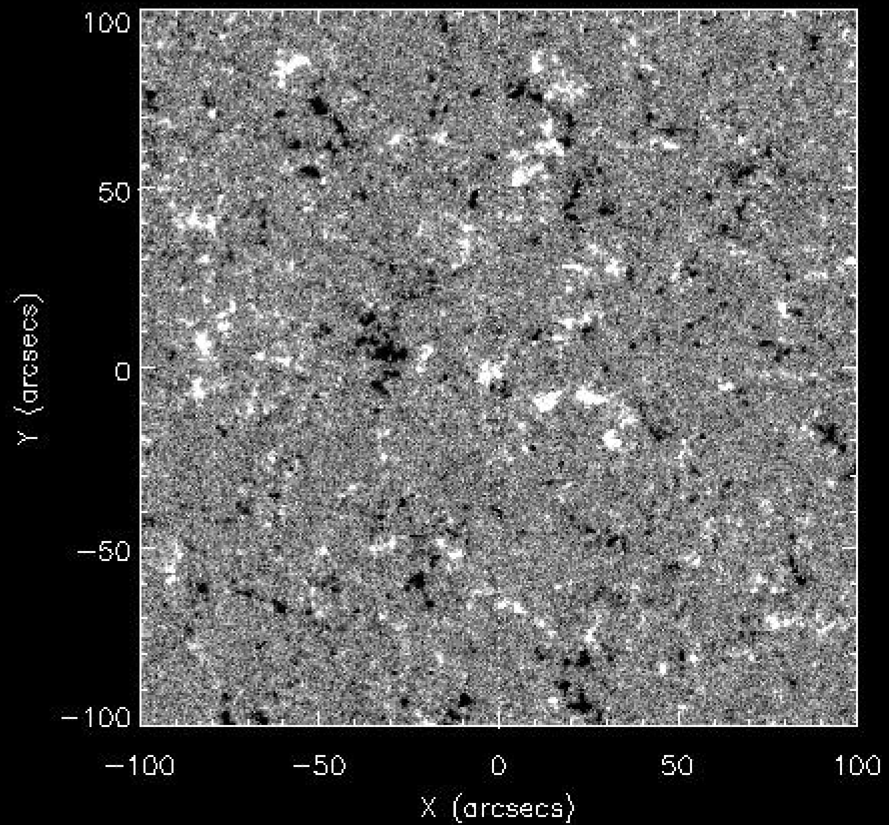


Virtual View of Solar North Pole
at 20 deg from solar equatorial plane

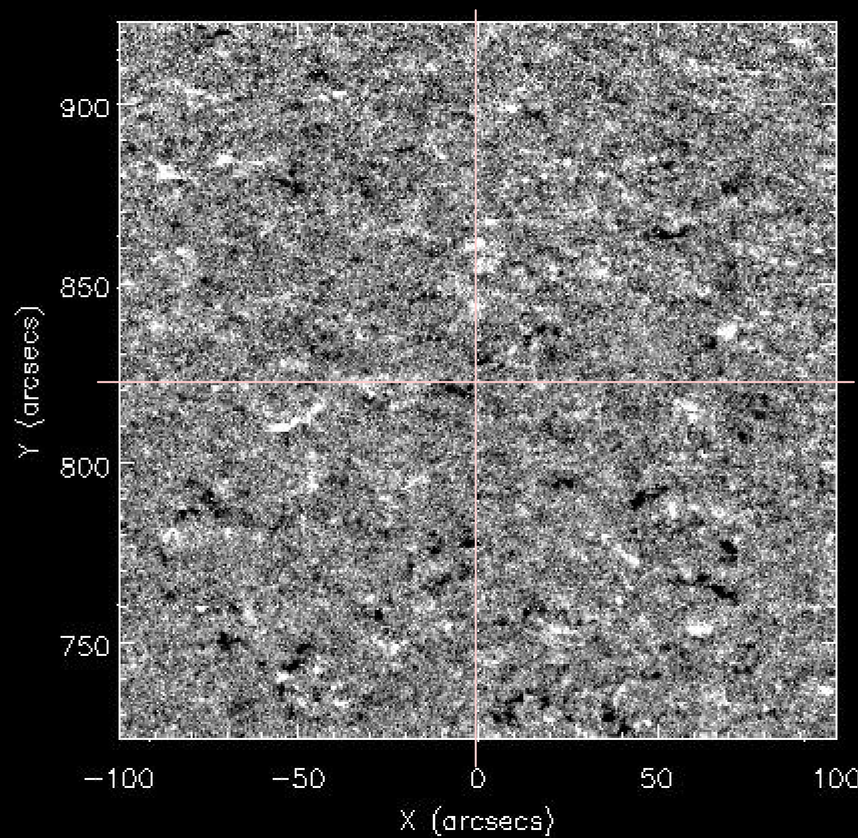


Data from a single FITS data of HMI/SDO 45s-cadence Longitudinal Magnetic Field

Disc center

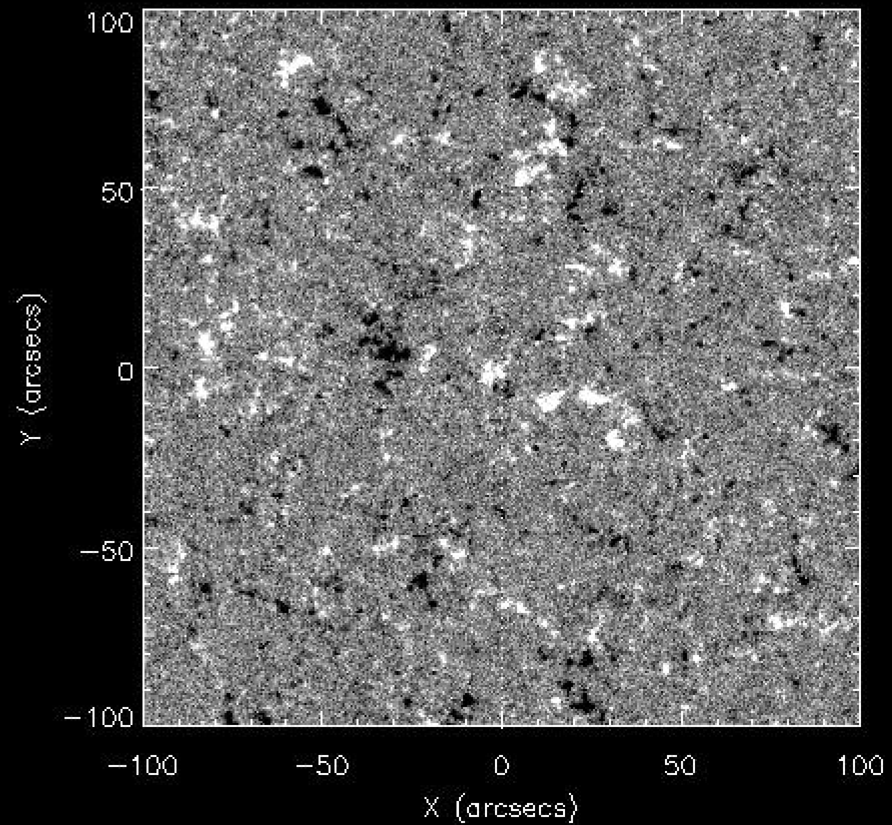


Virtual View of Solar North Pole
at 30 deg from solar equatorial plane

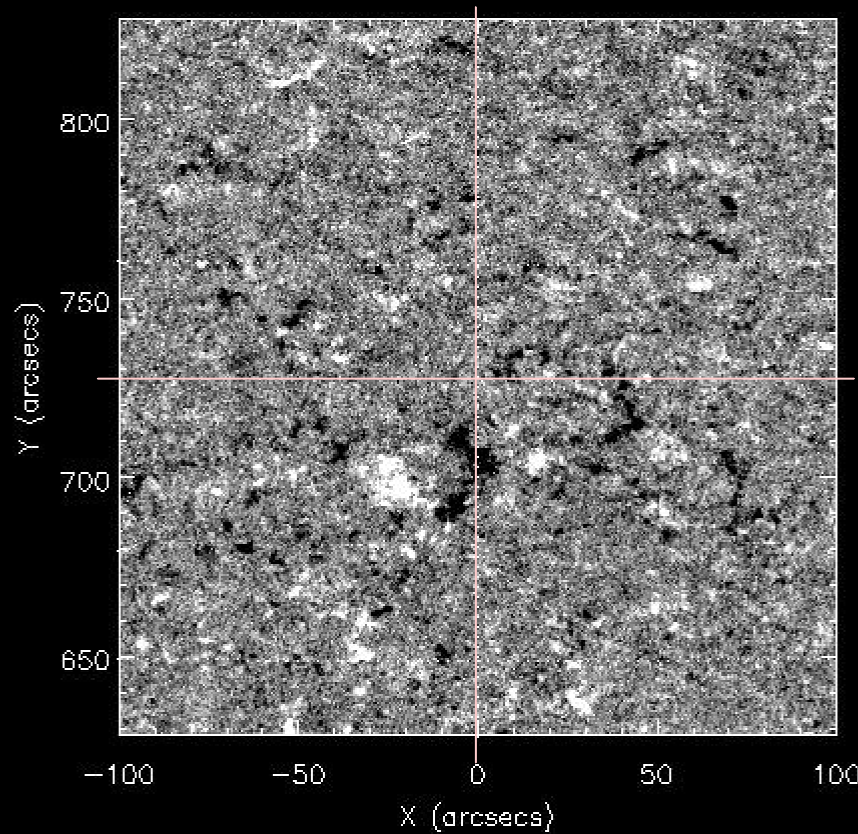


Data from a single FITS data of HMI/SDO 45s-cadence Longitudinal Magnetic Field

Disc center



Virtual View of Solar North Pole
at 40 deg from solar equatorial plane



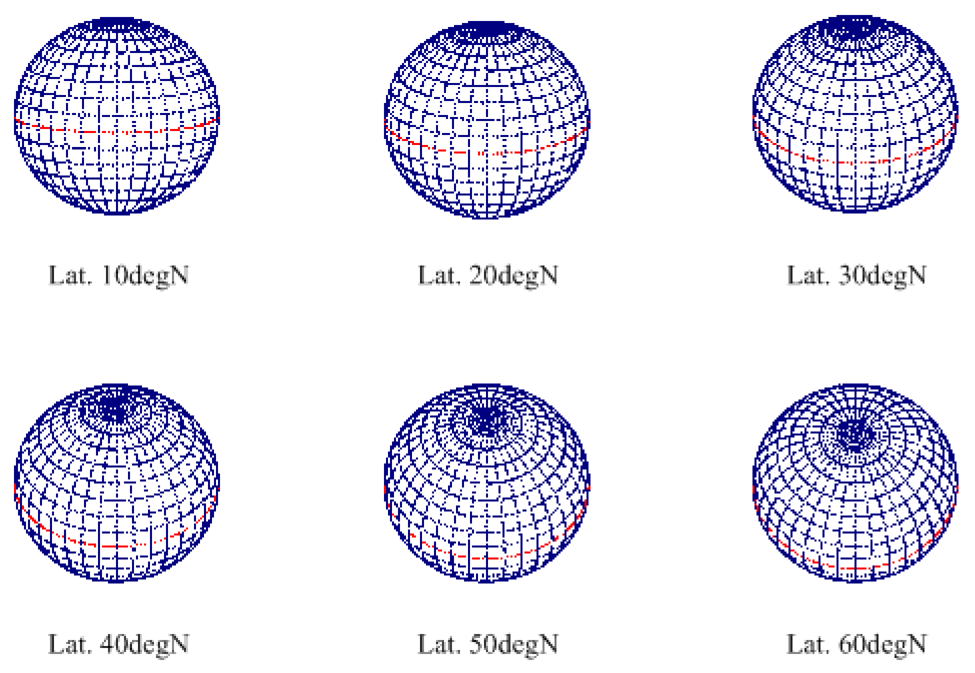
Data from a single FITS data of HMI/SDO 45s-cadence Longitudinal Magnetic Field

Requirement for average data recording rate

- Data Recording Rate: ~100 kbps (Total)
- Estimation for a model case (preliminary)
  - Helioseismology/B-field observations ~ 50kbps
    - Global helioseismology
      - 512×512(pixels) ×3(bit/pixel) /60(s)/1024(kbps/bps) = 13 kbps ave.
    - Local helioseismology
      - 1024 ×1024 ×3 (bit/pixel) /60(s)/1024 = 51 kbps ave.
    - Magnetic (B) field
      - LOS B: 1024 ×1024 ×3(bit/pixel)/300s/1024 = 10 kbps
      - Vec. B:2048 ×2048 ×3(b/pix) × 16img /7200(s)/1024 = 28 kbps
  - EUV imaging spectroscopy ~20 kbps ave.
  - EUV/X-ray imaging ~20 kbps ave.
  - TSI monitor: ~1 kbps
  - Heliospheric imager ~ 1kbps by on-board summing
  - Others: probably negligible

Mission Requirements for Orbit Formation

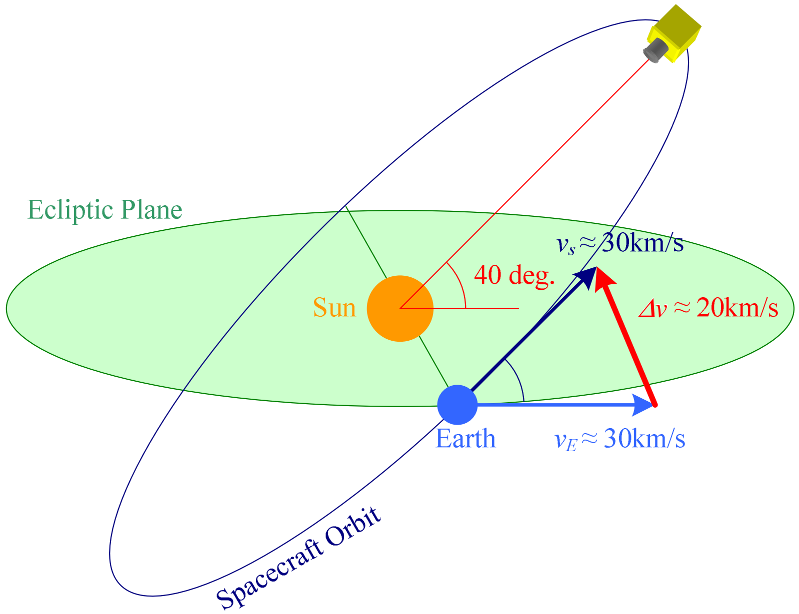
- To reach Solar Lat. 40° by early 2020's.
- Mass of Science instruments > 130kg.
- Data transmission rate > 300kbps @ 0.6AU.



View of the Sun from the High Solar Latitude

Challenge to Solar Lat. 40°

- Rough Estimation of the Launch Energy



$$C3 = (v_\infty)^2 \approx (20\text{km/s})^2 \approx 400\text{km}^2/\text{s}^2$$

(*cf.* $C3$ for the Jupiter Transfer ≈ 80km²/s²)

Techniques to Overcome the Challenge

- Trajectory Manipulation Techniques Available
  - Geometric Relation

    Take advantage of the tilt of the Solar equatorial plane against the ecliptic plane (about 7deg.). Choice of the appropriate launch date is important.
  - Launcher Capacity

    Launch energy is still the most contributing part. Launch a small spacecraft with a heavy launcher yields large launch energy.
  - Gravity Assist (Swingby)

    The most efficient trajectory manipulation method in the interplanetary cruise, which is widely used in various planetary missions.
  - Propulsion

    Usage of high efficiency propulsion system enables large velocity increment with less propellant.

Possible Options of the Trajectory Sequence

- Venus option (optionally surveyed)
- Jupiter option
- SEP option

Option-A orbit

- Near-Earth orbit using ion engine & Earth swing-by
  - Higher-priority orbit for Solar Physics, if technically feasible
  - High-data rate observations required for magnetic and helioseismic research
  - Limited imaging observations of the Sun during the use of ion engine if there is no active pointing mechanism on the payload
  - Launch opportunity: every 0.5 year
  - 40° inclination from solar equatorial plane,1AU distance, synchronized with Earth
  - It takes ~5 yr to achieve the target orbit.
- Jupiter swing-by + Earth swing-by (ballistic orbit)
  - Lower-data rate observations and lower spatial resolution before achieving target orbit
  - Observations are always possible except for swing-by operation
  - Launch opportunity: every ~1.1 yr
  - 36-40° inclination from solar equatorial plane,1AU distance, synchronized with Earth
  - Shorten the orbital period by Earth swing-by. It takes ~7 yr to achieve the orbital period of 1 yr.

How is the solar poles seen as a function of inclination angle?

i : inclination angle from solar equatorial plane

Rocket: H-II A-202

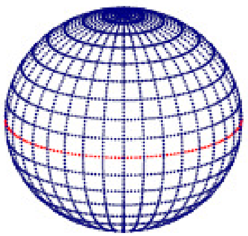
Cruise by Ion engine
in a shorter duration
compared with SO

~**5 years** for final orbit
of a=1.0AU, 1yr period

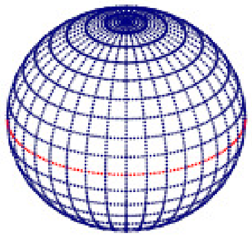
Ballistic orbit
Venus & Earth
Swing-by

~**3 years** for final orbit
of a=1.0AU, 1yr period

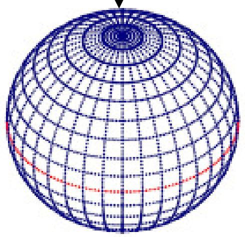
Possible by
Earth swing-by
only



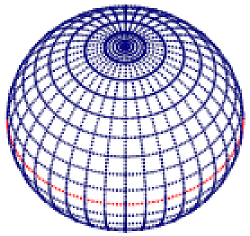
***i* = 20 deg**



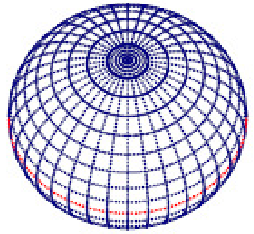
***i* = 30 deg**



***i* = 40 deg**



***i* = 50 deg**



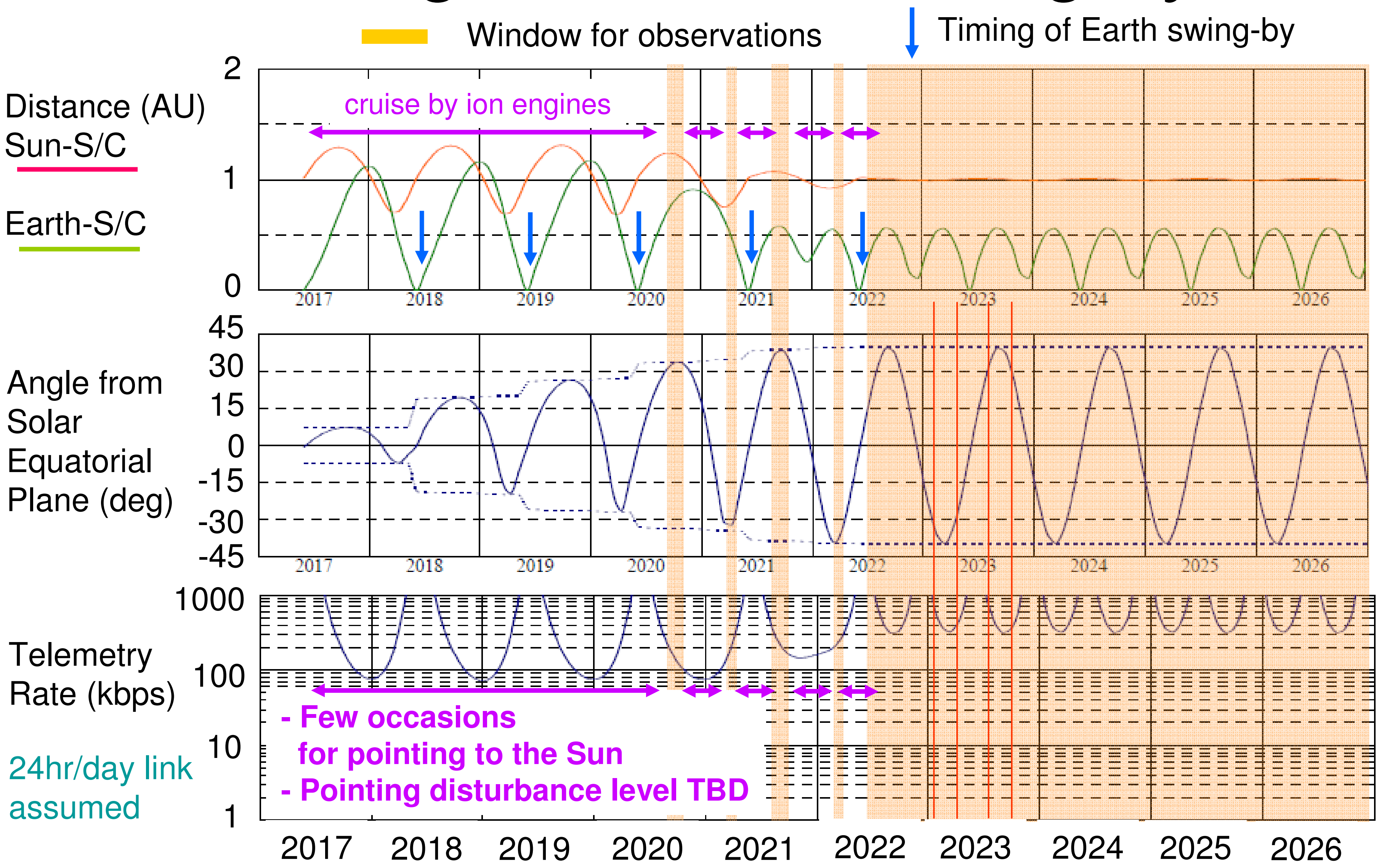
***i* = 60 deg**

Ballistic orbit
by **Jupiter & Earth Swing-by**
H-II A-202

~**7 years** for final orbit of
a=1.0AU, 1yr period

Ballistic orbit
Jupiter & Earth
swing-by
of long-duration
cruise (>7 yr)
Final period ~ 2 yr
H-II A-204

Ion engine + Earth swing-by

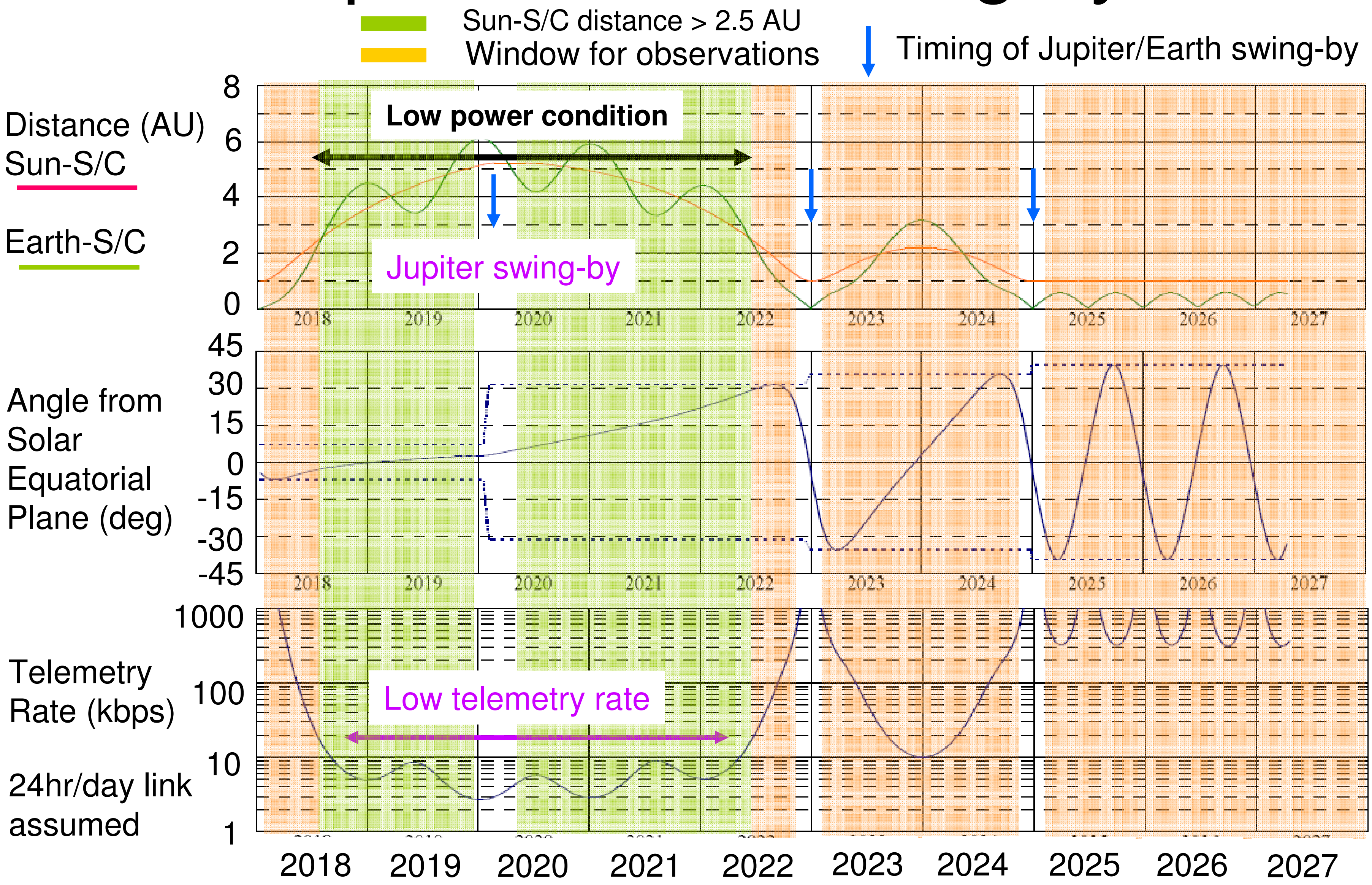


Priority in this case: reach max inclination as soon as possible

Technical Issues in spacecraft system for SEP Option

- Option-A - escaping from ecliptic plane
  - Kick-motor: no suitable kick motor for H II-A interplanetary mission
  - High power systems (~7 kW)
    - need high-efficiency power supply for operating ion engines toward further reduction of the S/C weight
    - need light weight solar array paddle (being developed in JAXA)
  - High telemetry rate in interplanetary space (~100 kbps data recording rate @0.6AU set as minimal required level)
    - not a high rate for NASA's S/C missions (slightly better in STEREO)
    - a key issue to enhance scientific return from helioseismology
    - needs downlink stations for deep space at both northern and southern hemispheres
  - High thrust ion engines (120 mN max)
    - endurance test of ENG model being performed at JAXA/ISAS
  - Heat exhaust from high-heat-generating components
    - found to be little problems after a thermal design for a model orbit

Jupiter + Earth swing-by

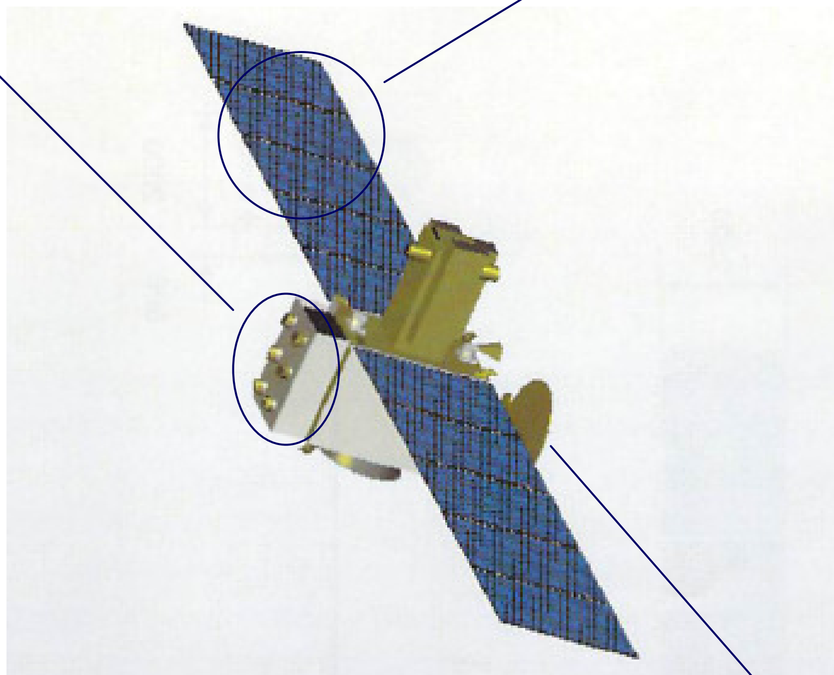


Priority in this case: reach max inclination as soon as possible

Jupiter Option Summary

- Compliance to the Mission Requirements
  - Reaches Solar Lat. 30° in 2022 (assumes launch in 2018), and finally achieves 40° .
  - Spacecraft's mass budget permits instruments > 130kg.
  - Data transmission rate > 300kbps @ high Lat. region (> 30°) (from 2025).
- Advantage
  - Conservative sequence which does not require electric propulsion system.
- Disadvantages
  - Long duration before the observation starts (> 4 years). Far from both Sun and Earth during the transfer.
  - Frequent observation of Solar Polar region (every a half year) starts from 2025.
  - Good launch opportunity (to reach 40°) may be infrequent.
    (the next launch window in 2019 achieves Solar Lat. 37° with the similar sequence)

Key Technologies for SEP Option



Conceptual Image of
SEP option spacecraft

Ka/X Communication System (1)

- System concept
  - –X-band system

    Mission requirement (300kbps @ 0.6AU telemetry) is achieved by redundant X-band system. It is equipped and well demonstrated in HAYABUSA, KAGUYA, etc.

  - –Ka-band system

    To enhance the scientific achievements, a single Ka-band system is additionally equipped.

  - –Link budget

Item	X-band	Ka-band	Unit
Frequency	8400	32300	MHz
Transmitter Power	40.0	20.0	W
Transmit Antenna Gain	36.5	48.2	dBi
Communication Distance	0.56	0.56	AU
Bit Rate	300k	1M	bps
Link Margin	**1.0**	**2.0**	**dB**

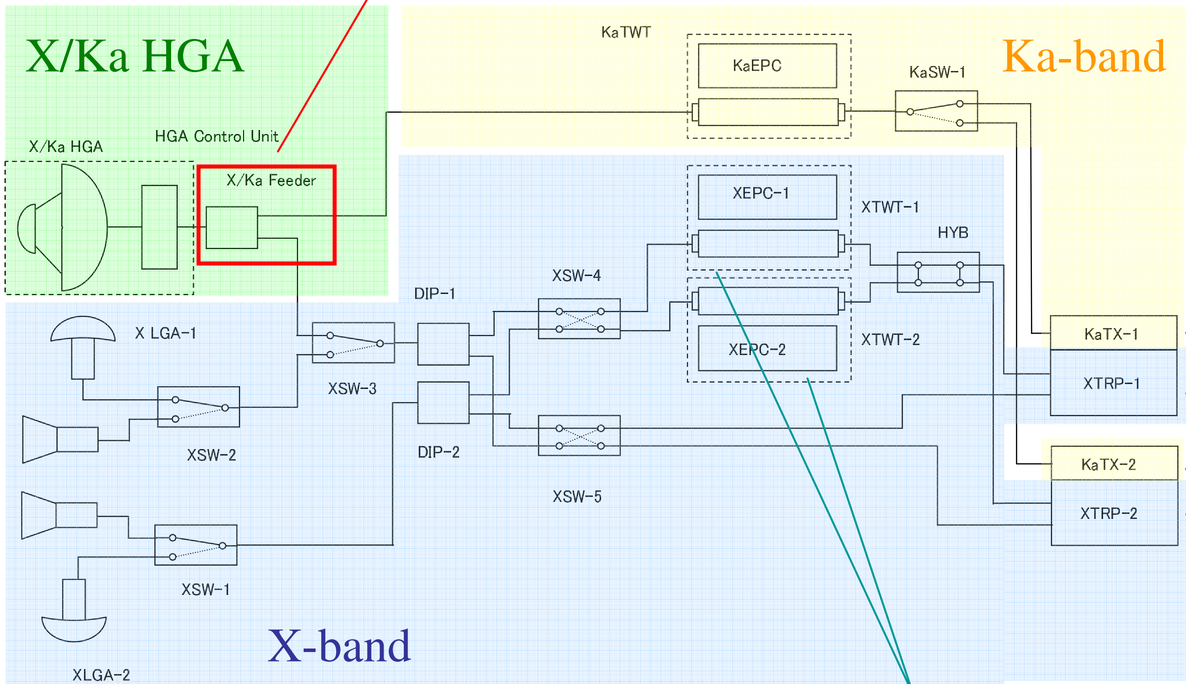
Receive C/N0	59.3	64.6	dBHz
Required C/N0	58.4	62.6	dBHz

Ka/X Communication System (2)

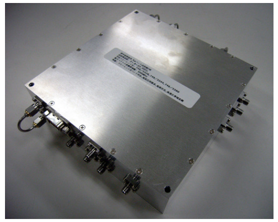
- System Configuration

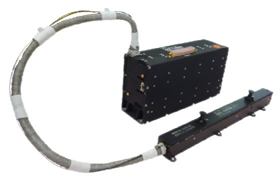
S/X HGA
(KAGUYA)

X/Ka Feeder (New Development)



Ka-TX (EM)





X-TWT (AKATSUKI)

X-TRP (AKATSUKI)

Improvements in ground segments also in progress.

SEP Option Summary

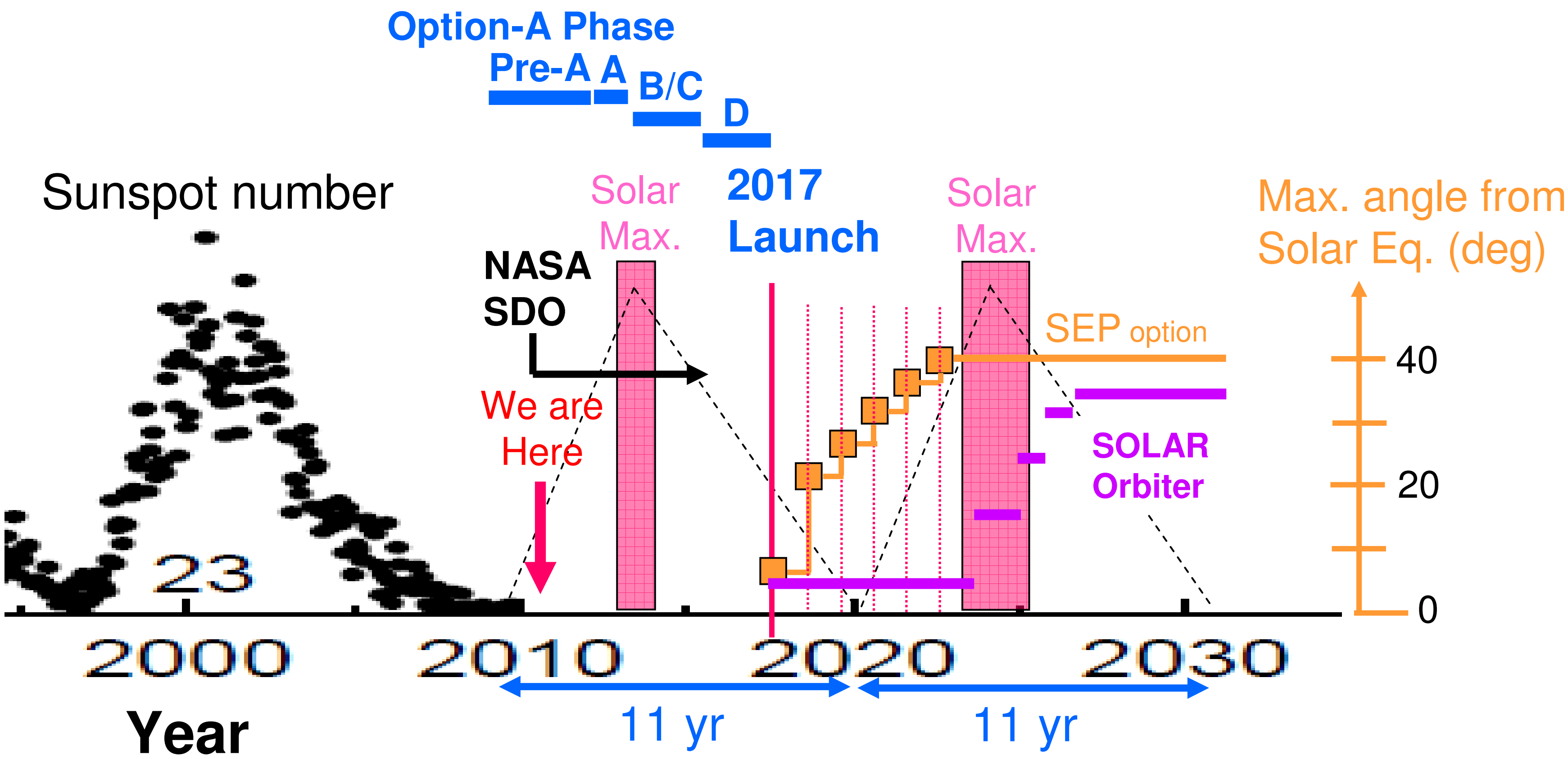
- Compliance to the Mission Requirements
  - Reaches Solar Lat. 30° in 2020 (assumes launch in 2017), and finally achieves 40°.
  - Spacecraft's mass budget permits instruments > 130kg.
  - Data transmission rate > 300kbps @ high Lat. region (> 30°) (from 2022).
- Advantages
  - Satisfy the most of the mission requirements.
  - Frequent launch windows (every half year).
- Disadvantage
  - Requires advanced technologies (electric propulsion system, etc.).

Trade-off Issues

- First Cost Estimate
  SEP (kick-motor + IES) > Jupiter (kick-motor) > Venus (no engines)
- Mission life: not clearly set, life-cost relation not yet investigated
- New development for orbit formation (assumption; use of H-IIA)
  SEP (kick-motor+IES), Jupiter (kick-motor), Venus (0.7AU test)
- Mission readiness
  SEP option may need an ENG mission using μ20 ion engine before SOLAR-C.
- Final latitude degree:
  40 deg (SEP) ~ 40 deg (Jupiter) > 25(2017L)-30(2020L) deg (Venus)
- Payload mass:
  130 kg (SEP) ~ 130 kg (Jupiter) << > 400 kg (Venus)
- Time for final orbit formation (1AU distance from the Sun)
  Jupiter (7 yr) > SEP (5 yr) > Venus (3yr)
- Others

Provisional Schedule

- If Option-A needs to look at the polar polarity reversal in 2020's in a good observing condition, the launch of 2017/2018 is required in SEP option.
- In the baseline Jupiter option, the polar reversal may occur before S/C reaches the maximum inclination.



Synergy among multiple spacecrafts

3D Scanning of Heliosphere by Multiple Spacecrafts

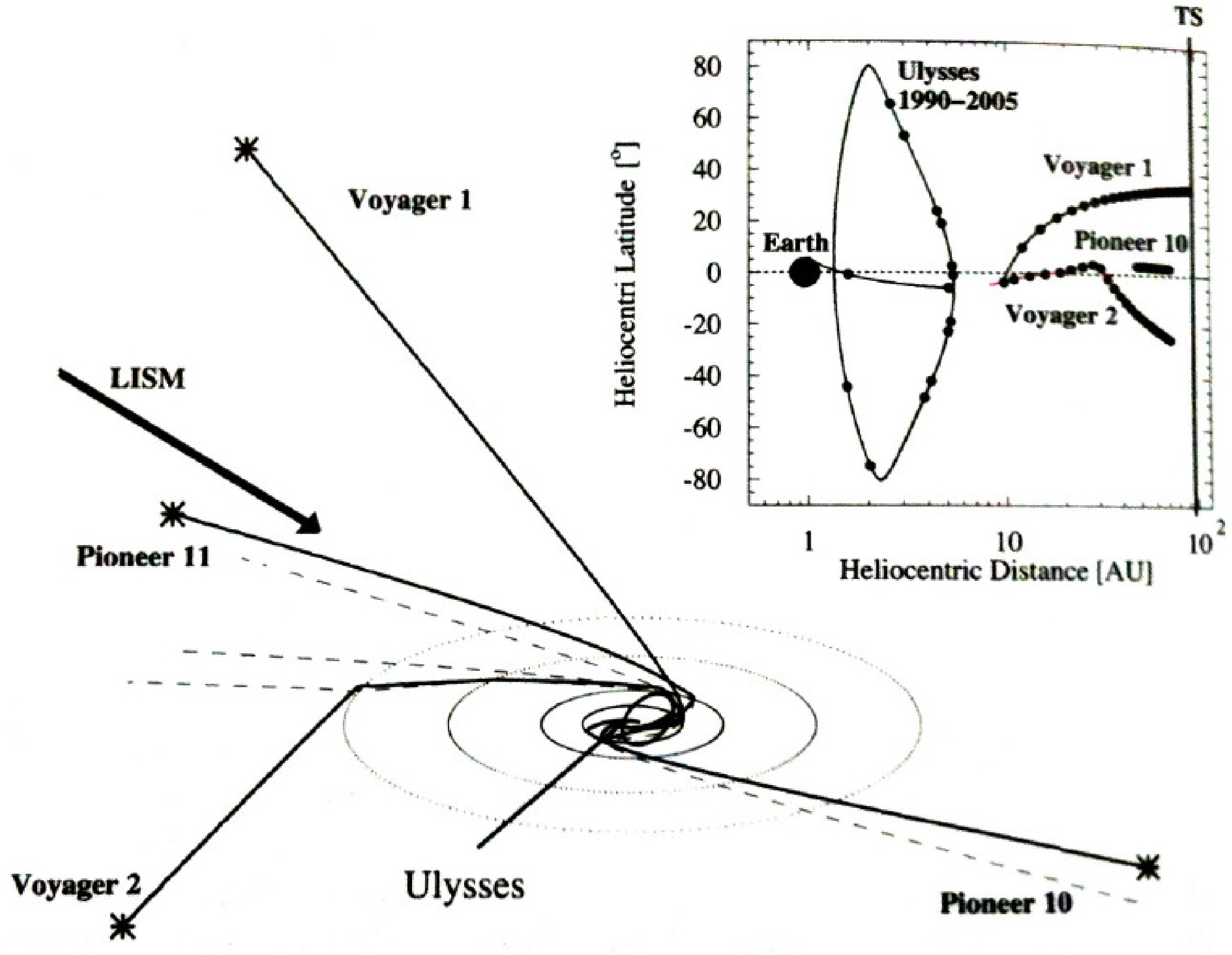


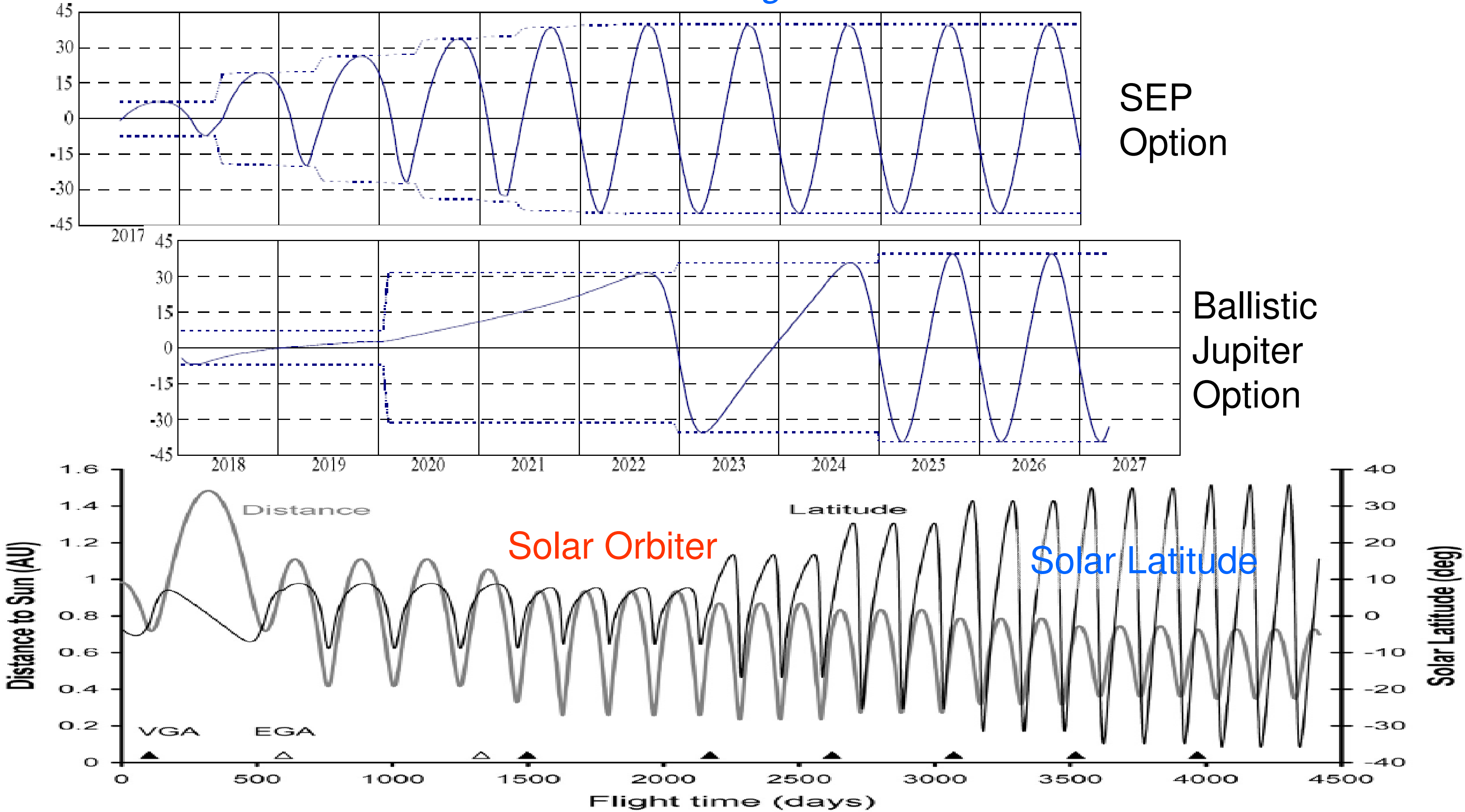
Figure from Heber & Cummings (2001)

Synergy between Option-A and SO

3D Scanning of the Sun by Multiple Spacecrafts

One spacecraft cannot cover both polar regions at one time.

Restriction: Instrument wavelengths need to be the same



Summary

- SOLAR-C Option-A is a mission to look at the Sun from an out-of-ecliptic orbit.
- We will observe features all over the latitudes on the sun and a wide rage of heliospheric latitudes at ~1AU:

  Magnetic fields, convection, internal rotation, meridional flows from magnetic and helioseismic observations, activity of upper atmosphere, source region of solar wind, and interplanetary in-situ measurements.
- Science in Heliospheric Physics has not been well discussed with heliophysics group. No updates since March.
- There are practical solutions for a spacecraft to enter a 40-deg inclination orbit with1-yr orbital period.
- The orbit with ion engines may be better at a glance, but there need many technical challenges. Due to this engineering issues, selecting the prime orbit for Option-A is not decided. Discussion is still going on.