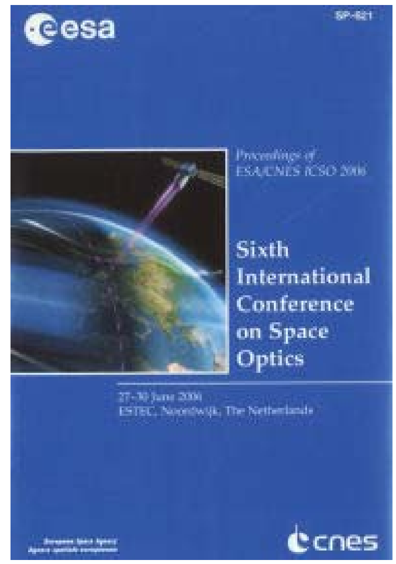
International Conference on Space Optics—ICSO 2006

Noordwijk, Netherlands

27–30 June 2006

Edited by Errico Armandillo, Josiane Costeraste, and Nikos Karafolas



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International Conference on Space Optics — ICSO 2006, edited by Errico Armandillo, Josiane Costeraste,
Nikos Karafolas, Proc. of SPIE Vol. 10567, 105670H · © 2006 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2308153

SEARCH FOR EXTRATERRESTRIAL PLANETS: THE DARWIN MISSION

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ABSTRACT

The ESA Darwin mission is primarily devoted to the detection of earth-like exoplanets and the spectroscopic characterization of their atmospheres for key tracers of life. Darwin is implemented as a free-flying stellar interferometer operating in the 6.5-20 micron wavelength range, and passively cooled to 40 K. The stellar flux is suppressed by destructive interference (nulling) over the full optical bandwidth. The planetary signal is extracted from the zodiacal background signature by modulating the optical response of the interferometer. The Darwin mission concept has evolved considerably in the past years. The original concept, based on six 1.5 m telescopes, has been replaced by more efficient designs using three to four three-meter class apertures. A novel 3D architecture is being evaluated, together with the conventional planar one, bearing the potential for significant volume and mass savings and enhanced straylight rejection. A number of technology development activities have been successfully completed, including optical metrology, optical delay lines, and single-mode infrared optical fibers. A second iteration of the Darwin System Assessment Study has been kicked off end 2005, aiming to consolidate the overall mission architecture and the preliminary design of the Darwin mission concept. This paper illustrates the current status of the Darwin mission, with special emphasis on the optical configuration and the technology development programme in the area of optics.

1. INTRODUCTION

The European Space Agency is currently assessing the Darwin mission, whose main objective is to search for terrestrial exoplanets, including the characterization of their properties and atmospheres, and the possible detection of biospheres through remote sensing. The scientific requirements and principles of operation of Darwin were presented in our previous report at ICSO in 2004 [2]. The Darwin concept has evolved considerably since then. Much effort has been devoted to the formulation of simpler architectures using three or four apertures, and in better understanding the factors limiting the sensitivity of the Darwin measurements. In October 2005, two parallel System Assessment Studies (SAS) have been initiated led by EADS Astrium and Alcatel-Alenia Space. The study objective is to reiterate the system architecture on the basis of the achieved technology development and the results of ESA internal studies [3]. The first phase of the SAS has been closed recently with the selection of two quite different baseline mission architectures, both achieving the challenging mission objectives. In the second phase of the study, preliminary mission designs will be established for the two selected concepts, including payload, spacecraft, launchers, orbit and ground segment. A mission design consolidation phase is expected to follow, covering the definition of a design, development, and verification programme, a redundancy scheme for successfully recovery from any mission anomalies, launch, transfer to L2, formation flying and resizing, and scientific measurement mode, and finally a mission cost estimate. In this paper, the current state of the Darwin mission is reviewed, with special emphasis on the optical configuration and the technology development programme in the area of optics.

Proc. '6th Internat. Conf. on Space Optics', ESTEC, Noordwijk, The Netherlands, 27-30 June 2006 (ESA SP-621, June 2006)

2. EVOLUTION OF MISSION DESIGN

2.1 Configuration studies

The hexagonal array, as established from the first System Assessment Study in the year 2000, has been the baseline Darwin mission until 2004. It consisted of an array of six 1.5 m free-flying telescopes, arranged in a hexagonal configuration around a central beam combiner hub [4]. The hexagonal array is characterized by an excellent stellar rejection capability, since the interferometer transmission increases only as θ^4 for a small off-axis angle θ. However, this advantage comes at the price of a high number of spacecraft (eight in total), leading to high system and operational complexity. Internal studies have been carried out to assess whether simpler arrays of three or four collectors could meet the scientific objectives of the mission, in spite of their shallower θ^2 null. Simulations have shown that a θ^4 null is an asset only for the nearest targets, for which stellar leakage is the dominant noise source at all wavelengths. For the majority of the Darwin targets, leakage is only a concern at the shortest wavelengths (approximately 6 to 9 micron). At longer ones, the major disturbance is the local zodiacal background, to which θ^2 and θ^4 architectures are equally sensitive [5]. In turn, arrays with 3-4 collectors have a number of performance advantages. They allow efficient use of the fairing volume, making it possible to use large (three-meter class) apertures. Three to four beams can be combined with relatively simple, more photon efficient beam combination schemes as compared to the hexagonal array. High modulation efficiency turns out to be the most important selection criteria for the interferometer architecture. The reduced sensitivity at short wavelength has an impact for spectroscopy, in particular on water absorption measurements at 6.5-7.2 micron. The Darwin science bandwidth has been extended up to 20 micron, which allows measurements at part of the broad water absorption line at 28.6 μm.

The Three Telescope Nuller and X-array

The overall system cost and complexity of an array are expected to increase with the number of spacecraft involved. ESA has investigated systematically the properties of arrays with three apertures (Three Telescope Nuller, TTN [6]). This is the minimum number of apertures required to implement background chopping. This study was partly driven by the observation that four spacecraft could effectively be accommodated on two medium class launch vehicles (e.g. Soyuz). Note that for TTN nulling requires phase shifts of 0°, 120° and 240°. Initially, two TTN configurations have been studied as reference, namely the linear TTN (LinTTN, where the apertures are collinear and equally spaced), which is the most efficient in the detection phase, and the equilateral TTN (eqTTN, where the apertures are at the corners of an equilateral triangle, with the hub at the center) for spectroscopy. Considering the high desirability of having a single configuration for both the detection and spectroscopic missions, the orthogonal TTN (oTTN) has been brought forward, where the three apertures are located on the three corners of a square, with the hub at the centre. Its properties are intermediate between those of LinTTN en equilateral TTN. The absence of rotational symmetry in oTTN makes it easier to locate the planet. Methods for the efficient combination of three beams have also been addressed, considering that coaxial beam combination (using beam splitters) allows a maximum efficiency of 75% for three beams. Multi axial beam combination has been proposed, where the three beams are directly injected and combined into a single mode waveguide [6]. To the purpose of the system study trade-off, the contractors have included the four-aperture X-array concept, currently studied by the TPF team at JPL [7]. The four apertures are located in the corners of a rectangle, with the beam combiner spacecraft in the centre. This is the only known architecture where the angular resolution can be adjusted without degrading the nulling performance. High resolution is required for accurate localization of planets. Also, it increases the frequency of the planet signal upon array rotation, which could allow calibration of systematic errors, the so-called instability noise [7]

2.2 Planar and Emma Arrays

Any of the configurations discussed above can be realized as a planar or 3D (Emma) array. These two architectures differ significantly in term of achievable sky coverage, intersatellite distance requirements, straylight issues, and collector satellite and relay optics implementation. In the planar architecture, the spacecraft fly in a common plane normal to the line of sight. Radiative transfer between s/c is minimized, since all hot thermal shields are nominally in the same plane. However, extensive baffling of the relay optics is required to block straylight from the hot sunshields at long baselines. The instantaneous sky coverage of the planar TTN is the ± 45 degrees cone centered in the antisun direction. The science signal is relayed from the collector s/c to the hub as collimated beams.

A three-dimensional Darwin architecture has been proposed in 2005, which is closely related to A. Labeyrie's hypertelescope concept, and is named Emma after Charles Darwin's wife. The collector s/c are located on the surface of a paraboloid, while the BCS is at its focus. A preliminary trade-off study indicates that the optimum focal length of the paraboloid will be in the order of 1 km. The collector optics consists of a spherical mirror, whose focal length matches that of the underlying paraboloid, and that serves as beam transfer optics to the hub. The instantaneous sky coverage of Emma is a hollow cone covering approximately angles between about 30 and 70 degrees from the anti-sun direction. However, almost the whole sky can be accessed during one year. The Emma design is relatively immature as compared to other interferometer architectures and is currently being assessed in the detail during the ongoing system studies. Its main advantages as compared to the planar design are i) simple collector s/c implementation: a spherical mirror replaces the telescope and the relay optics of the planar architecture, ii) the hub serves as an out-of-plane reference for metrology, which simplifies the control of the array geometry, iii) better sky access, targets are available for up to six months per year. More "easy" targets can be observed as compared to a planar architecture, increasing the number of stars surveyed and planets characterised during the mission. Conversely, Emma requires a more complex beam receive optics at the beam combiner level. Moreover, beams will be have rather large wavefront errors when the array is operated at long baselines (i.e., for distant and/or cold targets), which need to be corrected.

3. DARWIN technology roadmap

Based on the outcomes of the first Assessment Study in 2000, ESA initiated an extensive technology development programme (TDP) to bring Darwin-related technology to a maturity level by the mission definition phase. The TDP addresses challenging technology developments in three key areas: mid-infrared optics with low WFE, deep nulling interferometry at 40K, and formation flight (FF). In this section, we report on the status of the programme's optical technology development activities. The Technology Plan is re-examined periodically to keep consistency with new programmatic developments, improved understanding of the mission requirement and needs, and results from completed technology activities. In particular, following the outcome of the ongoing System Assessment Studies, the technology development plan shall be reviewed and brought in line with the baseline system design.

3.1 End-to-end simulator

The Darwin end-to-end simulator will be used through the whole Darwin project lifecycle to verify expected performance, to assess and minimize the impact of system dynamics on nulling, and to generate input data streams for development and testing of planet retrieval post-processing software. In the FINCH (Fast Interferometer Characterization) activity, EADS Astrium Friedrichshafen has developed a high-fidelity optical beam propagation code, FINCH/OPT, which computes the null output signal under dynamical perturbations of the optical system. The dynamics of selected optical components, or groups thereof, can be linked to a detailed model of the Darwin Guidance and Navigation Control System (FINCH/GNC), which includes formation flying and internal control loops such as OPD and tilt stabilization. FINCH/GNC was developed by EADS Astrium Toulouse. In the RESSP activity (Reconstruction of Exo-Solar System Properties from nulling interferometric data), a team led by Alcatel Alenia Space is developing the Darwin source generation and post-processing software. ORIGIN is an observation scene generator with an interface to FINCH/OPT. It generates a layered dataset containing the disk of the target star, its planetary system, its exo-zodiacal dust cloud and fore- and background emission from local zodiacal dust, galactic emission and, possibly, faint galaxies. FITTEST (Filter for Interferometric Test data and Terrestrial planet Exploration Software Tool is responsible for the detection and spectroscopy of planets, starting from Darwin raw null data and configuration housekeeping data. FITTEST solves for the most likely position and spectral content of a single planet, based on a Bayesian global maximization under constraints of intensity positivity, and smoothness of the planetary spectra with wavelength. The case of multiple planets is addressed by iterating the algorithm while the positions and spectral features of the already detected planets are updated with the knowledge of the latest detected one. The FITTEST algorithm is currently being tested for its ability to retrieve planetary signals in the presence of low-frequency noise, and interference from planetary interlopers in multiple systems. The Darwin end-to-end simulator will be the result of the integration of the ORIGIN, FINCH/GNC, FINCH/OPT and FITTEST software. It is expected that this simulator will be made available, via ESTEC, to the community involved in the development of Darwin within 2-3 years.

3.2 Optical metrology

In the frame of the High Precision Optical Metrology (HPOM) activity, an industrial team led by EADS Astrium GmbH (D) has developed the longitudinal and lateral metrology devices needed for Darwin formation flying. Longitudinal sensing is provided by an absolute laser metrology system, determining the absolute distance between hub and collector s/c with an accuracy of 32 micrometers rms at a sampling bandwidth of 10 Hz. Two different systems have been developed, based respectively on a dual-wavelength and a frequency-sweeping interferometer. A fine lateral sensor however has also been developed to an accuracy of 32 micrometers rms at 10 Hz over a full +/- 5 mm measurement range. Finally, a relative laser metrology system has been developed, measuring incremental changes of the path length between the hub and the TF to an accuracy of 2 nm $Hz^{-1/2}$ at a sampling bandwidth of 10 Hz. This activity was successfully completed in May 2006. Performance tests have been carried out in a modified thermal vacuum chamber such that inter-satellite distances of up to 10 meters can be simulated, including relative FF motions up to 2 mm/s. In this environment, all metrology devices have proved to perform better than the original specified.

3.3 Achromatic Phase Shifters

An activity for the development of achromatic phase shifters (APS) for Darwin has been awarded to a team led by the Institut d'Astrophysique Spatiale (IAS) (F). The main requirement on the APS is that it shall have the potential to provide a rejection rate of 1E-6 or better in the 6-18 μm spectral range (goal: 4-20 μm), with a transmission of better than 95%. Three APS systems have been selected for breadboarding. Two reflective concepts exploit the reversal of the electric field at reflection, and at focus crossing. These methods can produce only π phase shifts, as required by for example the X-array. The third APS concept makes use of a stack of three dispersive wedge plates (Ge, ZnSe and KRS-5) to compensate the dispersion characteristics, as done with achromats. Non-π phase shifts can be produced with this device. Note that for example, TTN requires 120° phase shifts. All three APS devices have been built and characterized. The reflective APS devices will be tested in a nulling configuration at short wavelengths (2-3 micron). A dedicated 100 K nulling testbench is being prepared for the final validation of all APS devices under cryogenic conditions and broadband illumination at 6-20 micron.

3.4 Fringe sensor

In order to maintain a deep null despite environmental disturbances (relative displacements of the flyers, vibrations, thermal effects), OPD must be measured at sub-nanometric accuracy, with a frame rate of 10 Hz. A team including Kayser Threde (D) and ONERA (F) has been in charge of developing the DarWin AstRonomical Fringe sensor (DWARF) for this purpose. The selected DWARF concept operates at visible wavelengths, with the provision for an additional, near-IR channel for redundancy. Beams are coherently combined in the image plane. OPD, tip-tilt, defocus, and higher-order aberrations are simultaneously estimated from the resulting fringe pattern, using phase diversity techniques. Wavefront sensing capabilities are required to calibrate phase errors arising from the process of coupling aberrated beams into a fiber. This effect cannot be measured directly by the fringe tracker. A three-beams test setup has been built including an optical system with which controlled amounts of aberrations can be introduced in one beam. Performance tests carried out at ONERA have demonstrated the validity of the all-in-one focal plane approach to accurately measure aberrations of the multiple-aperture instrument. The DWARF breadboard has proved to be compliant with the requirements, except for real-time defocus measurement at 10 Hz for which real-time algorithms need further developent. This activity was concluded in September 2005.

3.5 Optical Delay Line

The Optical Delay Lines (ODLs) have the task to stabilize and equalize the optical path lengths between the DARWIN science beams, without introducing any optical asymmetry that might degrade the nulling performance. Main critical requirements include a path length stability of better than 1 nm RMS at a control bandwidth of 10 Hz, over an optical path length range of +/-10 mm. To achieve these performances, it is assumed that the appropriate metrology signal is made available to the control electronics commanding the delay lines. Two parallel contracts led respectively by TNO (NL) and Contraves Space AG (CH) have been placed aiming at designing, manufacturing and testing delay line units compatible with the DARWIN optical requirements, at vacuum and 40 K temperature operating conditions. The ODLs shall be representative in form/fit/function of an engineering model.

The team led by TNO developed a concept where a cat-eye optical element is guided by an active magnetic suspension system. The Contraves design is based on a corner cube optical element, guided by a passive flexure mechanism suspended in an isolation stage. In both cases, the ODL moving mass is less than 0.7 kg, and coarse actuation is provided by a single-stage voice coil device, simplifying the control electronics compared to a typical dual-stage delay line configuration. Both teams have carried out successfully tests of the critical subsystems at cryogenic temperatures (optical elements, actuator, and guiding mechanism). At present, both consortia are conducting development test activities for the complete optical delay line system at ambient and at low temperature. Finally, after successful development tests the ODL performance will be validated at the required DARWIN cryogenic temperature of 40K.

3.6 Far-IR Linear Detector Arrays

Impurity band conductors (IBC) – e.g. Si:As – are regarded as the present baseline detector for the Darwin mission, in view of their high Quantum Efficiency (> 50% over the entire spectral range), low read noise (less than 10 e-) and low Dark Current (< 25 e- sec-1 pix-1). However, they require cooling to a few (~6-8) K with leads to heavy system cost and mass penalty, and to mechanical vibrations that are difficult to isolate from the optical bench. A development contract has been awarded to an industrial team including ACREO (S) and IMEC (B), with the goal to establish and demonstrate the performance of a detector meeting the Darwin requirements at the highest possible temperature. The selected technology is Quantum Well Infrared Photodiodes (QWIP). Initial theoretical modeling gave hope that the Darwin dark current requirements could be met around 16 K. Two array demonstrators have been manufactured, optimized for the shortest and longest Darwin wavelengths. Test on the finished sampled where made last year. Dark current measurements did not meet the requirements, but the reasons of the discrepancy from theory are understood. It is expected that further development may reduce dark current to the right order of magnitude. However, the quantum efficiency of these devices is low, even after the implementation of a dedicated on-pixel grating to allow polarization-independent absorption. This proved to rule out these sensors to Darwin. Dark current optimization is currently being pursued since QWIP technology is likely to find broad application in both Science an Earth Observation missions. In parallel to this activity, IMEC (B) is investigating the potential to rise the operational temperature of IBC detectors. The design of the demonstrator, including different geometrical pixel configurations, is almost complete and requires further processing recipe optimisation of the buried contact to avoid severe dopant diffusion into the active pixel area. In addition, the readout circuit design is shared with the QWIP activity. The final demonstrator should be ready by the end of the year 2006.

3.7 Single-mode fiber optics

Optical fiber technology is an enabling technology for Darwin. It is known that wavefront errors as small as a few tens of nanometers rms will degrade the Darwin nulling performance. In theory, wavefront errors could be simply removed by propagating the recombined beam through a short length of single-mode optical fiber, thanks to the fiber's modal filtering properties. At the time of our previous report at ICSO, single mode fibers operating at the Darwin wavelengths did not exist yet. Two parallel activities, led by EADS Astrium GmbH (D) and TPD/TNO (NL), were successfully concluded end of 2004 and early 2005 respectively, delivering and testing first samples of single-mode step-index fibers for Darwin. In more detail, the EADS Astrium team manufactured 35 fiber samples using different materials and processing techniques. GaAsSeTe (GAST) chalcogenide fibers were produced, suitable for operation in the 5-10 micron range, featuring high quality in terms of core shape and material homogeneity. Single-mode operation has been demonstrated at 10.6 micron, with typical losses (including Fresnel ones) of 73.5 dB/m (with V=0.76 at 10.6 micron). The team also developed fibers made of poly-crystalline silver halide (AgBrCl) for operation at wavelengths up to 20 micron. The crystalline structure of AgBrCl makes fiber manufacturing considerably more difficult than for chalcogenide glasses. The samples exhibit larger core defects and irregularities than the glassy ones. However, single-mode behavior at 10.6 micron has been demonstrated, with attenuation (including Fresnel losses) of 23.2 dB/m (V=1.34 at 10.6 microns). The quality of AgBrCl fibers can be improved by systematic optimization of material purity and manufacturing process, which is recommended as follow-up activity. The team led by TPD/TNO developed TeAsSe (TAS) chalcogenide fibers, with an operational range of 4 to 12 micron. Single-mode fibers of very good quality have been obtained, with typical attenuation of 10-18 dB/m. Both activities have shown the need to have high absorption coatings applied on the cladding external surface, in order to damp leaky modes that tend to propagate through the fiber because of the finite cladding diameter dimension. Suitable absorbing materials have been identified for both chalcogenide and silver halide fibers, and their effectiveness has been demonstrated experimentally. In addition both activities have demonstrated that on the contrary to theoretical predictions, i.e. a few mm is required length to damp the leaky modes assuming infinite cladding diameter, the fibers need to be longer than 20 cm to damp all leaky modes and behave as a single mode fiber.

3.8 Fiber Coupling Technologies

The maximum achievable coupling efficiency for a non-obscured uniformly illuminated circular aperture is less than 80%, due to the mismatch between the Airy disk profile of the focused incoming beam and the approximated Gaussian profile of the fundamental mode of the single mode fiber. Two parallel contracts have been awarded to teams led respectively by Contraves (CH) and KDA/Sintef (N) to identify and breadboard advanced concepts for coupling optical radiation into single mode waveguides that minimizes the total insertion loss. Both teams are carrying out the detailed design of a proof-of-concept demonstrator operating at near infrared wavelengths. Presently, analyses show that a coupling efficiency larger than the theoretical maximum of about 80% is possible taking into account implementation losses (e.g. optical losses due to the additional optical elements, manufacturing tolerances and alignment errors).

3.9 Integrated optics for Darwin

At thermal infrared wavelengths, a number of optical functions relevant to interferometry have been realized and demonstrated using integrated optics (IO) technology. A team led by IMEP (F) has been awarded an activity to identify materials, and develop manufacturing technologies for single-mode IO components operating in the 4-20 micron spectral range. Cryogenic operation at 40K was not a requirement in this activity. Both conventional dielectric waveguides and metallic hollow waveguides concepts have been addressed, together with possible manufacturing technologies. Metallic hollow waveguides (MHW) and thin-film dielectric waveguides were selected for actual realization and testing. Elementary linear and curved waveguides, T-junctions and a two-beam combiner have been characterized. The MHW samples have proven to be extremely effective as modal filter allowing for nulling ratios between 10^3 and 10^4, although they operate in single polarization only. Metallic hollow waveguides would be capable of operating in the 4-18 micron wavelength range but suffer from high coupling and intrinsic propagation losses that prevent its use for more complex functions. The waveguides produced during the study showed a typical transmission of only 1% over a length of 1 mm. Dielectric waveguides based on Tellurium glasses have a better potential in this respect. The critical issues for dielectric waveguides are the composition of a pair of glasses suitable for the design of a waveguide and their purification in order to minimize absorption bands. The activity was concluded in March 2006.

3.10 Future Developments

At this stage of the Darwin project, the prime goal of the TDP is to develop a nulling breadboard operating under conditions representative of Darwin (40K, in vacuum, and covering at least a representative part of the Darwin science bandwidth 6-20 µm). The use of this cryogenic breadboard is twofold: while the demonstration of the required nulling level under realistic conditions is a key driver in itself, the optical quality of breadboard components can ultimately only be judged by their performance in interferometric measurements. The breadboard shall integrate a number of optical components from already executed technology development activities. The overall architecture of the breadboard, and the design of specific subsystems, will depend on the outcome of the system level studies and other relevant development activities. In particular, the choice between three or four beams is still open, which in turn influences for example the Achromatic Phase shifter (APS) design. Off-line calibration of instability noise within the interferometric data reconstruction software (FITTEST) is currently being investigated. A positive result from this activity may allow relaxation of current tight null stability requirements. A second major goal of the future developments for Darwin is certainly the establishment of broadband, low-loss IR wavefront filter, whatever design (integrated optics, dielectric or photonic crystal fibres) is eventually selected, and adequate testing facilities. A further key driver of technology development for Darwin is the reduction of design complexity with substantial benefit for both mission cost and mass budget. A starting point might be to reduce the sub-bands in which the science wavelength range is split, due to chromatic limitations of wavefront filters and APS devices. A number of already available Darwin components will need to be developed to a full form, fit and function demonstrator (Technology Readiness Level 5). This includes, e.g., anti-reflective coatings for fibres and beam shaping optics to enhance coupling, or necessary passive optical components like polarizers, splitters etc.

4. CONCLUSIONS

Since our previous ICSO report in 2004 [2], the Darwin study has made considerable progress with respect to reducing the complexity of the mission while at the same time ensuring that its very demanding objectives are met. The output from these studies as well as the results from a considerable number of concluded technology activities have been fed to the currently running System Assessment Studies. After evaluation of a large number of different system architectures, two architectures have been proposed for more detailed study until autumn 2006. Following the outcome of the ongoing System Assessment Studies, the technology development plan shall be reviewed and brought in line with the baseline system design.

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