Systems Engineering Technical Excellence in Commercial Spacecraft Hosting of the NASA TEMPO Instrument

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The TEMPO Systems Engineering (SE) team delivered NASA's first Earth Venture Instrument or EVI (cost-capped, PI led) to Geosynchronous Orbit (GEO) as NASA's first complex commercially hosted payload through tailoring of NASA's SE processes in a pathfinding effort that is now achieving revolutionary Earth Science at a fraction of the cost for a dedicated mission. The cost/schedule centric, just-in-time, commercial production-line approach differs significantly from NASA's one-of-a-kind R&D approach as do the realities of serving as a secondary payload to the Host's primary, revenue-generating transponder payload. The NASA SE team balanced cost, schedule, technical quality, and risk against the commercial partners' SE process to lead the diverse, cross-organizational team (composed of NASA, Ball Aerospace, Harvard-Smithsonian Astrophysical Observatory, Carr Astronautics, US Space Force, Maxar Technologies, and Intelsat) to mission success within the Host's 3.5-year sprint from contract award to launch. The effort represented another step towards commercializing Earth orbiting missions, to free NASA to push the technology and exploration envelopes.

One major challenge lies in providing a motivating enough business case that the commercial host's Board of Directors will allow the bid on a Pathfinder. Hosts almost universally wanted the instrument delivered before they would bid, introducing a considerable challenge in striking the right balance in interface design and environmental test definition for a cost-capped instrument built under a firm-fixed price contract needing efficient implementation. Another major challenge lies in implementing the Spacecraft (SC)-level integration and test campaign while maintaining a healthy risk posture to science requirements. Several other commercial hosting attempts have failed over the years, leaving few positive lessons learned available for use in decision making. The team struggled with a commercial process optimized for production-line similarity of rugged transponders and antennae payloads as compared to a sensitive optical science instrument and with culture differences that limited the level of NASA insight into the Host's interfacing systems.

To meet these challenges, the TEMPO SE team first undertook an arduous RFP development effort in parallel with Instrument development. The team conducted study contracts with 11 interested commercial vendors ranging from simple Q&A to year-long studies with a sub-set of 3. The studies helped identify the balance between NASA standards and commercial SE processes to codify in level 3 requirements and made the TEMPO design/test campaign accommodatable for Hosts. The team tailored the SE process and produced Interface Definition Documents or IDD's (one-sided ICD's), test concept documents, and suggested verification methods for reference to assist the bidding Hosts in scoping the effort and as a jump start to the coming fast-paced 3-year effort. The SE team levied a CDRL on the Host to develop a traditional ICD to confirm their understanding of the IDD's and to provide TEMPO insights to Host interfaces.

The SE team updated requirements with as-built/as-tested levels just prior to Request for Proposals (RFP) release and updated the contract with as-promised performance from the winning Host's proposal. In one of several examples, the RFP was updated with actual random vibe notches. The Host collaborated with the SE team in design of a Host-provided vibration isolation system that ultimately attenuated the requirement-violating levels. The study contracts resulted in several changes including TEMPO removing its radiator from the design and providing access to its thermal interfaces for the Host to control and learning that the optical attitude/pointing requirements were out-of-family with the more relaxed ones for commercial antennae resulting in more focus in the RFP and in the Evaluation Criteria.

The team tailored the SE process and required non-typical risk-reduction testing in the RFP Statement of Work (SOW) and suggested details in a test concept (reference) document. The testing lowered risk to the Host's critical path I&T schedule and thereby to TEMPO's attitude/pointing requirements that ensured proper control of the TEMPO scanner and quality data for the geolocation and sampling algorithms. The testing was contrary to the Host's normal production-line process, schedule, and resource expenditure. One set of tests was aimed at the first interface between TEMPO and the spacecraft-provided IMU utilizing a loaner Engineering Model (EM) IMU and the TEMPO Instrument Simulator. The testing uncovered several incompatibilities that were corrected and ensured proper coordinate transformations between the IMU manufacturer, the Host, and TEMPO. The testing laid key groundwork for successful post-integration testing and on-orbit operations.

The TEMPO SE/SME team executed intensive, non-typical risk-informed-decision-making. In one of many examples, the team accepted verification by-analysis in lieu of by-test for the EMI/EMC Radiated Susceptibility requirement. The cost/schedule efficient normal commercial Host process involves cursory testing on a production-line unit with little front-end planning. A conservative scattering analysis indicated a narrow-band exceedance, justifying a test. Test design was considered and found insufficient to provide data needed to supplement the analysis. The Host then completed a more thorough analysis that indicated compliance to the TEMPO requirement with adequate margin. When TEMPO questions on model validation were not answered to a sufficient level of detail (Host is not organized to provide detailed insights to typical customers, nor to execute special test and model runs to provide evidence of validation), the SE team reviewed TEMPO requirement margin. The team confirmed test data on TEMPO's sister instrument was to higher levels for items of concern, TEMPO's most sensitive equipment is additionally shielded under MLI, and predicted levels at this equipment are small relative to the requirement, confirming significant margin and rationale for verification by analysis.

TEMPO is now in a truly revolutionary Phase E science campaign, providing results at a neighborhood scale. The TEMPO science team has 400+ early adopters from federal, state, and local air quality agencies, health organizations, non-profits, and international partners. TEMPO was selected as one of the top 200 inventions of 2023 by Time Magazine, featured in the 2023 White House Office of Science & Technology Policy Demo Day, featured by news outlets including in an NBC news segment ("New NASA Satellite Could Improve Air Quality by Tracking Pollution"), and garnered more hits to the NASA website than any other project (as of 8/2023) with its First Light press release. TEMPO serves as the North American component of an international constellation of air quality monitoring satellites that includes the Korean GEMS (launched Feb 2020) monitoring Asia and the European Sentinel-4 (expected to launch in 2024/25). A TEMPO-like instrument is planned for GeoXo with launch in the next decade to ensure TEMPO's legacy.