National Aeronautics and Space Administration

EXPERIMENTAL VALIDATION OF SWARM ARRAY RESULTS USING MARS CUBE ONE (MarCO) DOWNLINK SIGNALS

(Spontaneous Concept)

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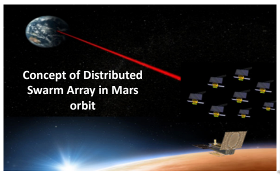
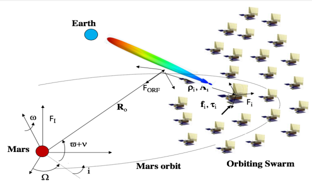
BACKGROUND/GOALS

The key strategic goals are to investigate the feasibility of constructing a deep space reconfigurable high-bandwidth communication system using swarms of satellites.

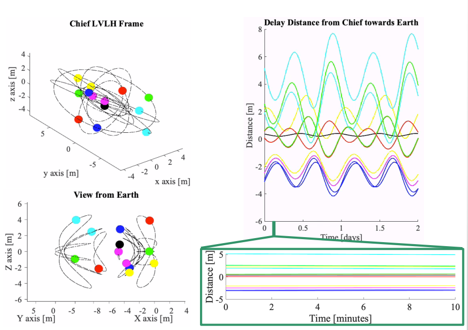


- Swarms of low-cost SmallSats can deliver a comparable or greater mission capability than large monolithic spacecraft, but with significantly enhanced flexibility (adaptability, scalability, evolvability, and maintainability) and robustness (reliability, survivability, and fault-tolerance).
- Our previous research investigated the feasibility of setting up a high-bandwidth swarm array in Martian orbit to ameliorate this communication bottleneck. We assumed the swarm array elements to be CubeSat-sized spacecraft, similar to MarCO. The main conclusion of the study is that a high data rate downlink swarm array at Mars is feasible. Approximately, 30 MarCO CubeSats achieve MRO-level performance, and 95 MarCO CubeSats achieve 10X MRO-level performance. Spacecraft can be incrementally added to the swarm, with each launch. Therefore, no dedicated launch is necessary.
- MarCO A,B were launched with Insight on May 5th 2018. The CubeSats regularly (and sometimes simultaneously) transmitted signals phase modulated onto X-band carriers, including a strong residual carrier and data to Earth during launch, cruise to Mars, and during Insight's EDL. MarCO A,B's downlink signals (especially those received simultaneously) could be viewed as transmissions from a swarm array, composed of two elements.
- Our plan was to analyze the X-band signals coming from the two MarCO spacecraft to and extrapolate the results to Ka-band carriers to verify our approach. Studying these downlink signals will enable us to experimentally validate our understanding of swarm array performance and develop techniques to phase and delay compensate the swarm array at Ka-band frequencies, enabling it to approach theoretical phased-array performance. These experiments with real data will enable us to take the concept of a high-bandwidth-communication swarm array in Martian orbit closer to reality.

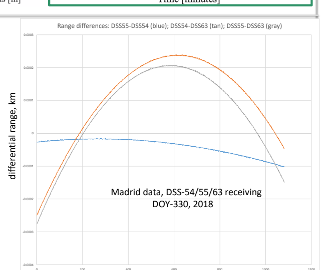
Corresponding Swarm Array geometry and mathematical model



- **Three-dimensional motion of Swarm Array in Mars orbit**
- **Short-term differential range (phase) between Swarm Array elements contain large second-order (parabolic) component**



- **Residual differential range between DSS-54/55/63 in Madrid**
- **Parabolic residual range consistent with Swarm orbital model**



OBJECTIVES

The objective was to: (1) Experimentally validate theoretical results on swarm array performance using MarCO A's downlink signals and the Madrid antennas DSS-63/55/54; and (2) Develop techniques to predict phased array performance, by demonstrating realistic carrier phase alignment using real spacecraft signals received operationally via DSN antennas

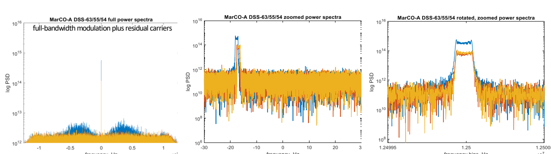
APPROACH

Using three of the Madrid DSN antennas (located several hundred meters apart) as proxies for three elements of a Swarm Array, and the downlink signals transmitted from MarCO A to simulate the phase reference distributed by the Master spacecraft or a suitable reference from Earth transmitted in two-way mode. **Invoking reciprocity, this approach provides exactly the same information for phasing up the Swarm Array, as would be obtained by maximizing the power received at a single ground-station from a three element phased array. T**his interpretation became necessary, since simultaneous two-way data from MarCO A/B was not available.

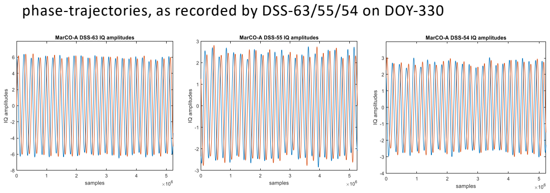
Two-way MarCO-A downlink data was recorded by the Radio Science Group's Open-Loop Receiver (OLR), at each of three DSN Madrid stations designated DSS-63/55/54. Signal processing algorithms were developed to process the data, and it was shown that accurate phase-calibration and phase-trajectory predicts can be obtained in a few seconds and used to maintain phase-coherence for the three proxy elements (three CubeSats plus the Master spacecraft) of a simulated Swarm Array. This suggests that frequent re-calibration will not be necessary when the orbital dynamics are well known, and when an accurate reference-signal is available from the ground in two-way mode, or from the Swarm Array Control spacecraft.

RESULTS

- Power spectra of MarCO A signal received by DSS-63/55/54, Madrid
- Simultaneous reception on DOY-330 1900-2000 UTC
- DSS-63 (70m antenna) signal 3dB higher than DSS-55/54 (34m antennas)

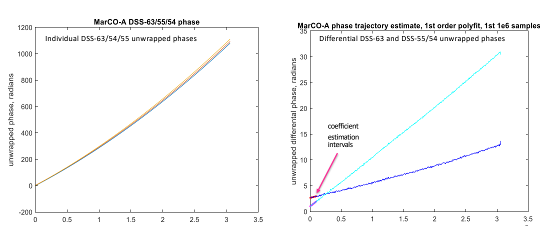


- Filtered time-series of residual carriers with differential range-induced phase-trajectories, as recorded by DSS-63/55/54 on DOY-330



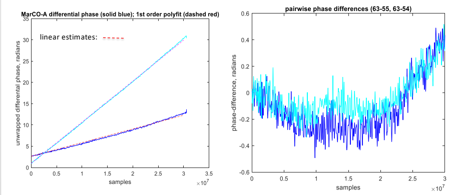
Real-Time Prediction (RTP) approach:

- Individual phase trajectories contain strong 1st and 2nd order components
- Difference phase between DSS-63 and DSS-55/54 found to be mostly linear near 1936UTC on DOY-330, with larger quadratic components earlier.

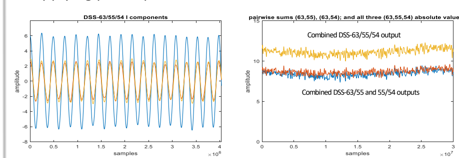


- Linear components were estimated over short time-intervals (~1/30 second)
- Residual phase-difference shows weak higher-order components at 1936UTC

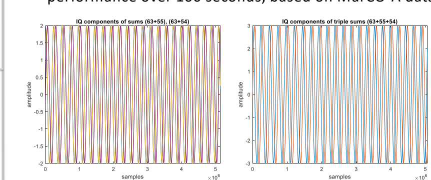
- Extrapolated phases found to be accurate to 100 seconds
- Residual phase found to be quadratic with small excursion



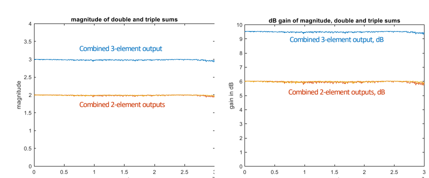
- Phase-difference predicts were applied to the time-series, resulting in well-aligned phases with small residual error
- Unequal power levels and amplitude fluctuations suggest applying phase-predicts to local oscillators on each element



- Simulated equal-power Swarm Array transmitters using extrapolated phase compensation show nearly lossless performance over 100 seconds, based on MarCO-A data



- Combining compensated oscillator outputs resulted in 2X and 3X increase of combined carrier amplitude
- Array power gain of 6dB and 9.5 dB, respectively, was demonstrated with processed MarCO-A data



Significance of Results and Benefits

- Two-way MarCO A data was recorded on DSS-54/55/63
- DSS-54/55/63 layout similar to Swarm Array in orbit
- Differential phase trajectories emulate Swarm behavior
- Residual carriers were used to obtain short-term estimates of phase for combining applications
- The MarCO A data serves as a proxy for transmission of reference signal from the "chief" spacecraft to the Swarm Array elements, or as a direct reference from the ground
- Individual phase trajectories were ~parabolic, as expected
- Differential phase found to be mostly linear, hence long-term phase predicts from short-term estimates were possible
- It was shown that long-term phase predicts enabled virtually lossless array combining for up to 100 seconds

These results, which were obtained from real spacecraft telemetry and operational antennas, imply that re-calibrating the Swarm Array on a timescale of minutes is feasible, enabling operational combining for high-EIRP downlink transmission.

Related publications:

[1] M. Quadrelli, R. Hodges, V. Vilnrotter, S. Bandyopadhyay, F. Tassi, S. Bevilacqua, "Distributed Swarm Arrays for Deep Space Applications," Proc. IEEE Aerospace Conference, Big Sky MN, March 2019.

[2] M. Quadrelli, R. Hodges, V. Vilnrotter, S. Bandyopadhyay, S. Finley, D. Kahan, "Experimental Validation of Swarm Array Results using Mars Cube One (MarCO) Downlink Signals," abstract accepted for IEEE Aerospace Conference, Big Sky MN, March 2020.

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