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Multipoint radio probe of the solar corona: The trans-coronal radio array fleet

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The Trans-Coronal Radio Array Fleet (T-CRAF) is a mission concept designed to continuously probe the magnetic field and plasma density structure of the corona at heliocentric distances of ≈ 2 – 10 $R_\odot$ (solar radius, $R_\odot$ = 695, 700 km). T-CRAF consists of thirty small satellites orbiting the Sun-Earth Lagrange Point L3 in order to provide thirty lines of sight (LOS) for ground- or space-based radio propagation studies. T-CRAF is divided into three sets of orbits, each with ten satellites: the first group provides LOS at a solar offset, SO (i.e. closest solar approach) of heliocentric distances 2–4 $R_\odot$ to provide continuous coverage in the middle corona, including initial slow solar wind acceleration; the second group of spacecraft probes the corona at SO = 4–7 $R_\odot$ to cover the region including transition to a supersonic slow solar wind; the outer T-CRAF group is positioned to afford coverage for SO > 7 $R_\odot$ as the winds continue to accelerate towards the Alfvén speed threshold. Each satellite is equipped with a multi-frequency (S-band, C-band, and X-band) linearly polarized transmitter. T-CRAF provides the capability to simultaneously measure the mean values and fluctuations of the magnetic field and plasma density within the solar wind, stream interaction regions, and coronal mass ejections (CMEs). Multiple downlink frequencies provide opportunities to use radio ranging (measurement of group time delay) and apparent-Doppler tracking (measurement of frequency shifts) to infer the plasma density and density gradient along each LOS. Linearly polarized signals provide the ability to detect Faraday rotation (FR) and FR fluctuations, used to infer the magnetic field and field fluctuations along each LOS.

KEYWORDS

solar corona, coronal magnetic fields, coronal plasma density, coronal mass ejection, radio astronomy, polarimetry

1 Introduction

Understanding the coronal plasma, in particular the plasma density and magnetic field strength and structure, is critical to understanding the foundational physics of the solar wind. Viall and Borovsky (2020) outlines several outstanding questions of solar wind physics that require detailed knowledge of solar wind plasma structure at heliocentric distances of <10 $R_\odot$. Within this region:

- The solar wind accelerates from subsonic to supersonic speeds, approaching super-Alfvénic speeds (reaching these speeds at the Alfvén critical point, typically $\lesssim 20\ R_\odot$, e.g. Wexler et al., 2021a);
- The fast solar wind typically reaches terminal velocity (at $\approx 10\ R_\odot$, e.g. Grall et al., 1996);
- equatorial and near-equatorial slow wind evolves from dense, closed magnetic structures to more tenuous, open magnetic field structures;
- MHD turbulence can contribute to energization of the corona due to dissipation of Alfvén waves;
- coronal mass ejections (CMEs) erupt, generating rapid evolution of the solar wind's plasma structure.

With the notable exception of Parker Solar Probe (*PSP*: Fox et al., 2016), no *in situ* spacecraft can probe this region of the corona; even PSP only visits perihelion ≈3 times a year, with relatively short observation intervals inside 10 $R_\odot$, and therefore can not provide continuous data coverage of this region. Space-based coronagraphs such as the Large Angle and Spectrometric Coronagraph (LASCO; Brueckner et al., 1995) on board the *Solar and Heliospheric Observatory* (*SOHO*; Domingo et al., 1995) and the Sun-Earth Connection Coronal and Heliospheric Investigation (SECCHI; Howard et al., 2008) instrument suites on board the twin *Solar TErrestrial RElations Observatory* (*STEREO*; Kaiser et al., 2008) spacecraft monitor this region; however, these primarily return total brightness white-light data which, unlike polarized brightness data, can not readily return information concerning the 3-D structure of the solar wind. The ability to provide continuous, 3-D images of the corona will not be available until upcoming NASA small explorer mission *Polarimeter to Unify the Corona and Heliosphere*[1] (*PUNCH*, PI: Craig DeForest) launches in 2025; however, the field of view will be 6–180 $R_\odot$, which lies outside the region of the middle (1.5–6 $R_\odot$, e.g. Seaton et al., 2020; West et al., 2022) and inner (<1.5 $R_\odot$) corona where many of these MHD processes and regime changes develop.

Data for the coronal magnetic field within this region is much more limited. The most reliable method for obtaining this information is radio remote sensing. For decades, radio remote-sensing methods have been used to probe coronal magnetic fields and, in recent years, some radio methods have even been used to return the internal plasma structure and magnetic field morphology of CMEs. These methods include detecting the gyrosynchrotron emission from the nonthermal particle distribution inside a CME and measuring the circular polarization of moving type IV radio bursts (Gopalswamy and Kundu, 1987; Bastian et al., 2001; Sasikumar Raja et al., 2014; Mondal et al., 2020) as well as measuring Faraday rotation using background linearly polarized radio sources (Bird et al., 1985; Kooi et al., 2014; Kooi et al., 2017; Kooi et al., 2021; Howard et al., 2016; Jensen et al., 2018). All of these methods, though, only provide sparse, sporadic measurements of the coronal or CME magnetic field structure. To answer fundamental questions such as:

- How is the solar wind accelerated?
- What is the origin and evolution of the meso-scale plasma and magnetic field structure of the solar wind?
- What are the dynamics of solar wind turbulence; where is the Alvén critical point and how does it evolve?
- How does the internal magnetic structure of CMEs evolve while they are still in their peak acceleration phase?

continuous, consistent measurements of the coronal magnetic field will be necessary.

2 The trans-coronal radio array fleet mission concept

The Trans-Coronal Radio Array Fleet (T-CRAF) is a mission concept designed to address these issues by continuously probing the magnetic field and plasma density structure of the corona at heliocentric distances of $\approx 2-10\ R_\odot$. T-CRAF consists of thirty small satellites orbiting the Sun-Earth Lagrange Point L3 in order to provide thirty lines of sight (LOS) for continuous ground- or space-based radio propagation studies of the corona as well as transient coronal phenomena such as CMEs. The idea to place permanent radio transmitters in orbit near L3 is not new. The concept was first discussed by Pätzold et al. (1995), Pätzold et al. (1996) and proposed as the "Solar Corona Sounders" (SCS) mission to an European Space Agency (ESA) call for mission concepts. Pätzold et al. (1995) suggested locating two spacecraft near L3, transmitting at 2.3 GHz and 8.4 GHz to continuously probe the corona. The orbits they proposed would provide two LOS with solar offsets (SO, distance from the heliocenter to the point of closest solar approach, or proximate point, along the LOS) at heliocentric distances 3–5 $R_\odot$ and 10–13 $R_\odot$.

Nearly 30 years later, the core mission concept—providing background transmitters to continuously probe the solar corona using radio propagation techniques—remains solid. However, several aspects require updating for contemporary planning, namely:

1. Number of spacecraft
2. Heliocentric distances range
3. One or more additional radio sensing frequencies
4. Broad helio-latitudinal coverage

1 https://punch.space.swri.edu.

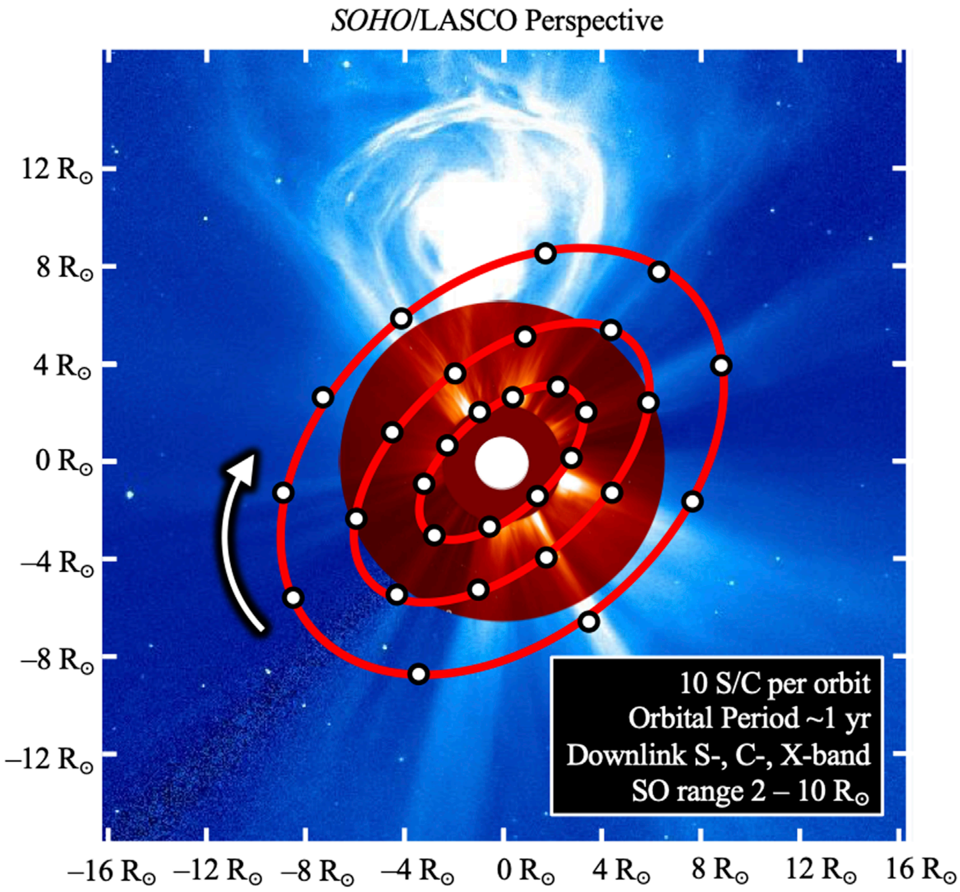

FIGURE 1
Illustration of potential spacecraft (S/C) positions for the Trans-Coronal Radio Array Fleet (T-CRAF) mission concept. There are ten spacecraft (white plotted points) per orbit (red). The inner, middle, and outer orbits have major axis lengths of $\approx 8\,R_\odot$, $\approx 14\,R_\odot$, and $\approx 20\,R_\odot$, respectively, and minor axis lengths of $\approx 4\,R_\odot$, $\approx 8\,R_\odot$, and $\approx 14\,R_\odot$, respectively. The arrow shows the direction of orbit. The white circle in the image center is the photosphere. The background shows a CME on 2000 February 27 as observed with the C2 (red) and C3 (blue) coronagraphs on board *SOHO*.

SCS was designed for only two satellites, each completing an orbit in ∼1 yr; consequently, most of the corona would remain unsampled at these heliocentric distances (e.g. while the apparent position of the satellites from Earth were off the eastern limb of the Sun, there would be no LOS off the western limb). Further, by only providing LOS with SO = 3–5 $R_\odot$ and 10–13 $R_\odot$, there is no way to sample the region between 5–10 $R_\odot$ where a number of important coronal transitions occur.

The T-CRAF mission concept requires thirty spacecraft divided into three sets of orbits, each with ten satellites: the first group provides LOS at SO = 2–4 $R_\odot$; the second group probes the corona at SO = 4–7 $R_\odot$; the outer T-CRAF group is positioned to afford coverage for SO $> 7\,R_\odot$. Utilizing ≈10 spacecraft per orbit, with orbital periods ∼1 yr, places LOS surrounding the Sun, providing the opportunity to simultaneously probe different regions of the corona (e.g. equatorial streamer belts, polar coronal holes, etc.). Also, injecting the spacecraft into three separate orbits (inner, middle, and outer) provides LOS measurements across the full range $\approx 2 - 10\,R_\odot$.

Figure 1 provides an illustration of the apparent spacecraft LOS geometry as viewed from the LASCO coronagraphs on board *SOHO*, which provides a similar perspective to those of ground-based receivers on Earth. The inner (red) and outer (blue) fields of view are provided by LASCO-C2 and C3[2]. These images show the spectacular CME that erupted on 2000 February 27. If a similar eruption occurred during this mission, the thirty spacecraft in this configuration would ensure multiple LOS through multiple regions of this CME, providing detailed information concerning the CME's plasma structure and its

2 These images are available at the *SOHO* public archive http://sohowww.nascom.nasa.gov.

evolution through the corona. These LOS would also provide critical measurements to evaluate restructuring of the corona after the outburst events.

3 Radio propagation methods with the trans-coronal radio array fleet

The T-CRAF mission is designed to provide enough background radio transmitters to allow continuous ground- or space-based radio propagation measurements of the corona at distances of $\approx 2-10\,R_\odot$. These measurements provide information on the solar wind speed and acceleration, plasma density and density fluctuations, and magnetic field strength and structure, as well as magnetic field fluctuations. A summary of these methods can be found in **Table 1**.

3.1 Solar wind speed and acceleration

The solar wind speed, V_{SW}, and acceleration can be calculated using a number of radio propagation methods. Detection of phase (Doppler) shifts using multiple frequencies to infer V_{SW} has been used for decades (see, e.g. Woo, 1978). Observations of radio intensity scintillation can also be used (Imamura et al., 2014). Because T-CRAF uses multiple downlink frequencies, we can use radio frequency fluctuations (FF) to infer V_{SW}. This method, as detailed in Wexler et al. (2019a), Wexler et al. (2020), requires calculating the FF variance, σ^2_{FF}, generated by density oscillations of length L_{RAD} advected across the LOS. The FF variance is then related to the solar wind speed according to Eq. 15 in Wexler et al. (2020):

$$V_{SW} = \frac{L_{RAD}}{\lambda r_e \delta n_e}\sqrt{\frac{\sigma^2_{FF}}{L_{LOS}R}} \qquad [\mathrm{m\,s^{-1}}] \tag{1}$$

where λ is the wavelength of the downlink signal, r_e is the classical electron radius, δn_e is the RMS electron number density fluctuation, L_{LOS} is the transverse correlation scale of the oscillations, and R is the effective length of the LOS integration path. Calculating the FF variance over a range in heliocentric distances then provides the speed profile necessary to measure acceleration[3].

3.2 Solar wind plasma density

T-CRAF's multiple downlink frequencies provide the opportunity to use radio ranging (measurement of group time delay) and apparent-Doppler tracking (measurement of frequency shift) to infer the plasma density and density gradient along each LOS. These methods provide information for the Total Electron Content, the column density of electrons in the corona:

$$\mathrm{TEC} \equiv \int_{LOS} n_e(s)\,\mathrm{d}s \qquad [\mathrm{m^{-2}}] \tag{2}$$

Radio ranging (also known as Differenced Ranging *Versus* Integrated Doppler, DRVID) measures the group delay time, Δt, from the spacecraft to the observer. For a signal with angular frequency ω, this is given as

$$\Delta t = \frac{S}{c} + \frac{q_e^2}{2\omega^2 c\epsilon_0 m_e}\mathrm{TEC} \qquad [\mathrm{sec}] \tag{3}$$

where c is speed of light, q_e is electron charge, ϵ_0 is permittivity of free space, m_e is electron mass, and S is the effective length of the LOS. S/c is simply the light travel time in a vacuum; consequently, the effect of the coronal plasma is represented by the second term. T-CRAF will provide multiple downlink frequencies; consequently, the differential time delay, $\Delta\tau$, between the group delay at one frequency (with ω_1) and the group delay at another frequency (with ω_2) can give the TEC directly:

$$\Delta\tau = \frac{q_e^2}{2c\epsilon_0 m_e}\left(\frac{1}{\omega_1^2} - \frac{1}{\omega_2^2}\right)\mathrm{TEC} \qquad [\mathrm{sec}] \tag{4}$$

For details of this method, see, e.g., Bird et al. (1994). Beyond providing a direct measurement of the TEC, radio ranging can also be used to study fractional electron density fluctuations (see, e.g. Woo et al., 1995).

The apparent-Doppler tracking method provides a means to infer plasma density gradients by measuring the frequency shifts, Δf, related to the rate of change in TEC:

$$\frac{\Delta f}{f} = -\frac{1}{c}\frac{\mathrm{d}S}{\mathrm{d}t} + \frac{q_e^2}{2\omega^2 c\epsilon_0 m_e}\frac{\mathrm{d}}{\mathrm{d}t}\mathrm{TEC} \tag{5}$$

The spacecraft Doppler motion contributes equally to all downlink frequencies; consequently, this can be removed *via* simple subtraction. The remaining frequency-dependent fluctuations are therefore a result of the plasma. For excellent demonstrations of these two methods, see, e.g., Jensen et al. (2016), Jensen et al. (2018).

3.3 Solar wind magnetic field

T-CRAF's linearly polarized, multi-frequency downlink signals provide another exciting opportunity: continuous measurement of coronal Faraday rotation (FR). FR is the rotation of the plane of polarization of linearly polarized light as it propagates through a magnetized plasma, denoted by $\Delta\chi$:

$$\Delta\chi = \left[\left(\frac{e^3}{8\pi^2\epsilon_0 m_e{}^2 c^3}\right)\int_{LOS} n_e \mathbf{B}\cdot\mathrm{d}\mathbf{s}\right]\lambda^2 = [\mathrm{RM}]\,\lambda^2 \qquad [\mathrm{rad}] \tag{6}$$

3 This requires assumptions for δn_e. Alternately, if the speed profile is independently known, this can be used to measure δn_e.

TABLE 1 Radio propagation effects and the corresponding plasma parameters that can be studied using the T-CRAF mission.

Observation method	Plasma properties	Example papers
Phase (Doppler) Shifts	V_{SW}	Woo (1978)
Intensity Scintillation	V_{SW}, n_e	Imamura et al. (2014)
Frequency Fluctuations	V_{SW}, δn_e	Wexler et al. (2019a), Wexler et al. (2020)
Radio Ranging	n_e	Bird et al. (1994), Jensen et al. (2016), Jensen et al. (2018)
Apparent-Doppler Tracking	δn_e	Jensen et al. (2016), Jensen et al. (2018)
Faraday Rotation	n_e, $B_\parallel$	Bird (2007), Kooi et al. (2022)
Faraday Rotation Fluctuations	$\delta B_\parallel$	Hollweg et al. (1982), Hollweg et al. (2010), Wexler et al. (2020)

where n_e is the electron plasma density, **B** is the vector magnetic field, and d**s** is the vector spatial increment along the LOS, in the direction of the observer. The physical constants e, ϵ_0, m_e, and c are the fundamental charge, permittivity of free space, mass of an electron, and speed of light, respectively. The terms in brackets are collectively called the Faraday Rotation Measure, RM, reported in rad m^{-2}.

Numerous FR observations have employed spacecraft transmitters, such as Levy et al. (1969), Stelzried et al. (1970), Volland et al. (1977), Bird (1982), Bird (2007), Pätzold et al. (1987), Bird et al. (1992), Efimov et al. (1993), Andreev et al. (1997), Chashei et al. (1999), Efimov et al. (2000), Jensen et al. (2013), Efimov et al. (2015a), Efimov et al. (2015b), Wexler et al. (2017), Jensen et al. (2018), Wexler et al. (2019b), Wexler et al. (2021a). FR observations using T-CRAF would provide significant improvements over these previous observations:

- T-CRAF provides the opportunity to continuously monitor coronal FR, no waiting for suitable spacecraft positioning (e.g. conjunctions);
- T-CRAF provides thirty LOS, removing uncertainties that result if only a single LOS is available;
- T-CRAF provides multiple downlink frequencies and the opportunity for continuous tracking, which can be used to remove $n\pi$ ambiguities in $\Delta\chi$ that result from phase wrapping for large RM;
- T-CRAF provides the opportunity to use radio ranging and apparent-Doppler tracking to infer the plasma density contribution to FR; therefore, the magnetic field inferred from FR will be considerably more accurate.

The first two points are crucial for using FR to probe transient events such as CMEs. All previous observations of CME FR using spacecraft transmitters have been serendipitous. Kooi et al. (2021) reported the only multi-LOS FR observations of a CME that were purposefully triggered based on the sudden eruption of said CME and they accomplished this using background radio galaxies. The primary advantage of natural radio sources (e.g. radio galaxies or pulsars) has always been their availability; on any given day, there are typically 50–100 linearly polarized natural radio sources available for FR experiments. The primary disadvantage of natural radio sources is that they produce a much weaker signal compared to spacecraft transmitters. T-CRAF provides the best of both worlds: continuous availability and strong signals. Kooi et al. (2021) was also the first paper to determine the absolute orientation of a CME's magnetic field using FR alone[4], which required FR observations along multiple LOS. T-CRAF has the potential to provide several LOS through CMEs off the solar limb (e.g. in **Figure 1**) and, critical for space weather applications, up to thirty LOS for Earth-directed CMEs.

Faraday rotation fluctuations (FRF) can also be measured and have been used to infer magnetic field fluctuations. Simultaneous observations of FRF and variations in TEC (e.g. Hollweg et al., 1982) indicate that magnetic field fluctuations dominate the FRF measurements. Consequently, the term that dominates the variance in RM is given by:

$$\langle \delta \mathrm{RM}^2 \rangle \approx C_{\mathrm{FR}} \int_{LOS} n_e^2 \left\langle \delta B_\parallel^2 \right\rangle L_{B_\parallel} \mathrm{d}s \qquad \left[(\mathrm{rad\,m^{-2}})^2 \right] \tag{7}$$

where $\left\langle \delta B_\parallel^2 \right\rangle$ is the variance in the amplitude of the magnetic field component parallel to the LOS and $L_{B_\parallel}$ is the auto-correlation scale length[5].

This can be used to estimate the RMS magnetic field fluctuations, $\delta B_\parallel \equiv \left\langle \delta B_\parallel^2 \right\rangle^{1/2}$. The ability to infer $\delta B_\parallel$ is important because it provides a means to calculate the wave flux density, e.g., for Alfvén waves:

$$F_A = \frac{1}{\mu_0} \delta B_\parallel^2 V_A \qquad [\mathrm{W\,m^{-2}}] \tag{8}$$

where V_A is the Alfvén wave speed. This provides a direct method for calculating the wave flux density, which is critical for addressing MHD turbulent dissipation models. For reviews of coronal and CME FR observations, as well as detailed discussion concerning the use of FRF to assess Alfvén wave flux densities or differential FR measurements to detect electric currents on the solar wind, see Bird (2007) and Kooi et al. (2022).

4 Wood et al. (2020) previously determined the absolute orientation of a CME by combining radio FR, white-light imaging, and *in situ* data.

5 $L_{B_\parallel}$ is one of the most difficult quantities to estimate. Hollweg et al. (1982) assumed that the magnetic field fluctuations were associated with Alfvén waves generated by perturbing magnetic flux tubes at the photosphere; therefore, they defined $L_{B_\parallel}$ as the mean spacing between flux tubes.

4 The trans-coronal radio array fleet spacecraft concept

Because the objective of T-CRAF's mission design is to provide enough background radio transmitters to provide continuous ground- or space-based radio propagation measurements of the corona and, therefore, do not require *in situ* or other remote-sensing instruments on board, the spacecraft themselves can be simple, low-cost radio transmitters. Ideally, each spacecraft would transmit a linearly polarized signal across multiple frequency bands. To optimize the signal-to-noise ratio (SNR), the S-, C-, and X-bands are required. There are three reasons for this selection:

1. Radio propagation effects scale according to frequency (as discussed in **Section 3**); consequently, multiple downlink frequencies provide a more accurate measurement (especially for FR and apparent-Doppler tracking measurements).
2. SO $< 6\ R_\odot$ require higher frequencies like C- and X-bands (e.g. Kooi et al., 2014; Jensen et al., 2018; Wexler et al., 2020) because the side lobes of the receiving antenna's beam response are smaller and, therefore, less susceptible to solar interference (e.g. solar flares, radio bursts, active regions, the Sun itself, etc.) that would dramatically impact the system noise.
3. At larger solar offsets, solar interference is not necessarily an issue; however, radio propagation effects are reduced due to smaller plasma densities and weaker magnetic fields. Therefore, smaller frequencies (S-band) are required.

5 The trans-coronal radio array fleet's potential for space weather forecasting

One of the exciting prospects of T-CRAF science is the ability to detect FR through Earth-directed CMEs and, thus, providing detailed measurements of the CME's magnetic field structure while it is upstream from Earth and well before it interacts with *in situ* spacecraft orbiting near L1. This poses two significant challenges:

- Earth-directed CMEs may only generate a weak FR signal. Due to the geometry between the CME's magnetic field and the LOS, and because FR is an integrated measurement, the measured FR may be very weak.
- Modern FR observations of CMEs off the solar limb (which provide a more ideal LOS geometry for FR studies of CMEs, e.g. Kooi et al., 2017; Kooi et al., 2021) typically take weeks to calibrate and analyze; consequently, these observations will not immediately return the CME's magnetic field structure, which is necessary for early warning space weather applications.

The first issue should be addressed with robust modeling of Earth-directed CME FR. Liu et al. (2007) previously simulated FR for a simple flux rope geometry and Jensen et al. (2010) simulated FR for a flux rope and sheath geometry. These modeling endeavors should be expanded to include modern MHD modeling or geometric reconstructions of CME structures (e.g. Wood et al., 2020), for a variety of CME morphologies and orientations to truly understand the feasibility of these measurements.

The second issue requires development of an advanced CME FR data reduction pipeline. It is only in the last few years that CME FR observations have been able to unabiguously return the CME's magnetic field orientation (Wood et al., 2020; Kooi et al., 2021). After T-CRAF is launched, it will provide ample opportunities to collect FR observations of Earth-directed CMEs. By building up a database of these measurements and supplementing this with a large sample set of simulated CME FR, machine learning methods can be used to develop this CME FR data reduction pipeline.

Once these issues are addressed, T-CRAF could become a powerful early warning space weather forecasting system using FR tomography. The thirty LOS, together, would provide a low-resolution FR image of the corona: an FR sky map. By taking advantage of simultaneous radio ranging and apparent-Doppler tracking measurements (**Section 3.2**), the plasma density contribution to the FR will be well known; consequently, each FR sky map could then be used to provide a 2-D representation of the corona's magnetic field, much in the same way as coronagraph images provide a 2-D representation of the corona's plasma density. As the Earth rotates around the Sun, the LOS will provide slightly different perspectives of the coronal structures they sample; consequently, an FR sky map time series could be combined using tomographic methods to generate a 3-D representation of the coronal magnetic field. This is similar in principle to using multiple perspectives (e.g. stereoscopic imaging using *SOHO*/LASCO and *STEREO*/SECCHI) to reconstruct the 3-D white-light morphology of coronal plasma structures. Because the T-CRAF transmitters would provide a strong downlink signal, they could be used to generate FR sky maps at a high cadence and, therefore, *T-CRAF* could quickly generate low-resolution FR tomographic scans suitable for studying fast, transient structures like CMEs. This rapid tomography could quickly return the magnetic field orientation of Earth-directed CMEs, which would revolutionize early warning space weather forecasting systems.

Such T-CRAF measurements would be complemented by other future missions, such as the *Multiview Observatory for Solar Terrestrial science* mission concept (*MOST*: Gopalswamy et al., 2021). The primary goal of *MOST* is to understand the magnetic coupling between the solar interior and the heliosphere. The *MOST* concept includes four spacecraft:

one each at L4 and L5, one ahead of L4, and one behind L5. These spacecraft will host a suite of remote-sensing and *in situ* instruments that will track transient and quiescent 3-D magnetic field structures (e.g. CMEs) within the inner heliosphere. The Faraday Effect Tracker of Coronal and Heliospheric structures (FETCH), one of the proposed instrument concepts for *MOST*, will perform spacecraft-to-spacecraft FR measurements of the solar wind upstream from Earth at SO < 0.5 AU using the four LOS provided by the four spacecraft (Wexler et al., 2021b; Jensen et al., 2021). FETCH's LOS will be nearly perpendicular to T-CRAF's LOS; consequently, the two missions, together, will provide important information about the evolution of solar wind structures upstream from Earth.

6 Recommendations to further develop the the trans-coronal radio array fleet mission concept

The T-CRAF mission concept requires further development. It will be necessary to simulate the T-CRAF orbital dynamics to understand the most cost-effective method to inject each spacecraft into orbit around L3. Pätzold et al. (1996) discuss the orbit design for the two-spacecraft SCS mission concept, noting that their mission concept could be implemented with a tandem launch or with two individual launches directly into the interplanetary trajectory, or *via* a geocentric transfer (GTO) park orbit. They studied many different transfer orbit options and determined that 2.5- and 3.5-year transfer orbits were most feasible. Similar orbital studies should be made to determine the most efficient launch method for T-CRAF.

After calculating the optimal orbits for T-CRAF, a mission cost analysis must be performed. The primary cost involved for this mission is likely launching the spacecraft fleet and providing each spacecraft with the required propulsion system to enter into orbit, making course corrections as necessary. While other *in situ* or remote-sensing instruments could, in principle, be added to each spacecraft, the core T-CRAF concept is to only include linearly polarized, multi-frequency radio transmitters. The technology for such downlink transmitters is mature and does not necessarily require additional development; consequently, the spacecraft and radio transmitters themselves may be relatively inexpensive.

It will also be necessary to model the radio propagation effects for both the quiescent solar wind and transient coronal phenomena such as CMEs. The expected values for radio methods (such as those listed in **Table 1**) should be calculated for different orbital geometries. This is important in order to determine the sensitivity required for receiving systems to effectively use T-CRAF. This would also provide insights into how many spacecraft are actually required to fully reconstruct the three-dimensional magnetic field structure of CMEs (e.g. using tomographic techniques), which is critical if T-CRAF is to be used as part of an early warning geomagnetic storm prediction system. These modeling efforts will also inform the T-CRAF transmitter design. A relatively large transmitter power will be necessary for the downlink signals to be readily detectable by simple ground- or space-based receivers. For transmitters generating a 100 W signal, the SNR is ≈68.8 dB and ≈89.9 dB for receivers (dishes with 15 m diameters) with a 10 Hz bandwidth at typical downlink frequencies of 2.3 GHz and 8.4 GHz, respectively, depending on the transmitter antenna design.

T-CRAF is designed to provide signals detectable by simple receiving systems; therefore, T-CRAF provides an opportunity to study the corona for a variety of observers, from major research facilities to colleges and universities. However, we also recommend developing a complementary receiving system in tandem with the T-CRAF concept. A dedicated facility with the receivers and resources necessary to continuously detect the downlink signals from all T-CRAF spacecraft will ensure continuous, consistent monitoring of the corona at heliocentric distance of $\approx 2 - 10\,R_\odot$.

By making T-CRAF transmitters strong enough to be readily detectable at Earth, though, this mission will be contributing to human-produced radio frequency interference (RFI). In particular, it will place thirty sources of RFI in close proximity to the Sun at frequencies coinciding with the frequency spectrum of some solar radio bursts (SRBs). However, most SRBs emitting at these frequencies are very close to the Sun, typically much closer than the 2 $R_\odot$ solar offsets provided by T-CRAF (e.g. Dulk, 1985). Also, SRBs have well-defined spectral and temporal characteristics, which would be distinguishable from the known downlink signals corresponding to T-CRAF spacecraft. Regardless, it will be important for this mission to engage the solar and radio astronomy communities during the design process to minimize the impact of T-CRAF on other science missions.

7 Summary

The Trans-Coronal Radio Array Fleet's (T-CRAF) thirty spacecraft provide the opportunity to continuously probe the magnetic field and plasma density structure of the corona at heliocentric distances of $\approx 2 - 10\,R_\odot$ using ground- or space-based radio propagation experiments (**Figure 1**). The low-cost spacecraft consist of linearly polarized radio transmitters broadcasting in the S-, C-, and X-bands, ideal for observing radio ranging, apparent-Doppler tracking, and Faraday rotation among other effects (see **Table 1**). We recommend simulating T-CRAF measurements for robust solar wind and CME models in order to fully understand the technical limitations for this mission (e.g. its ability to detect Earth-directed CMEs) and how to address them.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JK was responsible for the organization of this article and contributed to all sections. DW was also responsible for the article's organization and made contributions to **Section 2** through **Section 4**, and **Section 6**. EJ made contributions to **Section 3**, **Section 5**, and **Section 6**. BW made contributions to **Section 5**.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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