Optical Intersatellite Links Made Easier and Affordable by Precision 3D Spacecraft Localization via GPS/GNSS Constellations

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Abstract. The paper focuses on the emerging space-distributed multisatellite constellations, swarms and formations, which are increasingly proposed to carry out Missions demanding tremendous intersatellite information exchange rates, thus justifying the use of optical frequencies. The paper then addresses the critical issue of how to cope with the fast initial satellite acquisition needs, considering that the satellites will increasingly be injected in orbits leading to time-variable topologies, and that communication needs increasingly require minimizing link acquisition and reacquisition times during satellites handover. Solutions based on the partial use of the GPS data available on board the satellites and broadcast to all others are described. The mix of large and powerful satellites and of less capable microsatellites demands solutions which are tailored to the planned capabilities or even capable of complementing them.

1 Facing up to an Exciting, Ever-changing Scenario

The growing interest in LEO satellite constellations, most notably for science and remote sensing applications [2] as well as for communications with mobile and fixed terminals [1], [3], [11] and new forms of space distributed assets such as satellite swarms and formations, increasingly require that optical broadband intersatellite links be reconsidered in addition to rapidly reconfigurable interconnectivity. Indeed the consolidation of the engineering methodologies for building inexpensive minisatellites [4], microsatellites and nanosatellites, will progressively lead to a shift away from a ‘concentrated’ architecture, characterized by very few spacecraft, to a spatially ‘distributed’ one where many smaller spacecraft cooperate to achieve a level of operational performance which had previously been unimaginable [5], [6]. The orbital topology of these space distributed systems will differ greatly, depending on the Mission objectives and orbit control type. For example, the satellites of swarms and constellations are conceived not to be tightly orbit controlled, therefore the distances between satellites and the line-of-sight orientation will dynamically change, while those belonging to formations are, instead, strictly controlled in terms of spacing and l.o.s. orientation . The spatial distribution of these assets brings with it new communication requirements: while some application imply quite modests intersatellite information exchange rates, others- the more interesting ones – do imply very high data rates exchanged between satellites and, what is more worrisome, a fast switching of the data flow towards different cooperating satellites.

In essence, we will witness the development of re-addressable, dynamically evolving, space data networks where each node – a satellite belonging to a constellation, formation or swarm- 'talks' sequentially with the partner satellites at very high speed and with minimum handover delay.

2 Optical Links and Related Problems

Optical technologies are ideally suited to support high data rate intersatellite link, because of the much reduced dimensions of the equipment required compared to the microwave frequencies. However the gain which is feasible with optical frequencies is paid with very narrow beamwidths, something which has two well-known consequences:

a) the necessity of disposing of very fine pointing and tracking systems to co-align the transmitter and receiver optical boresights;
b) problems with the initial spatial acquisition, and reacquisition, of the other satellite with which two way communications must be established.

The first issue is typically addressed by means of optical systems that apply well-known radar tracking techniques (e.g.: monopulse, conical scanning, step tracking) or other continuous or pulsed beacon tracking systems: but all have in common the fact that, to have a fair chance of aligning the two transceivers in a finite time, the initial angular error between their optical boresights must be in the range of a few beamwidths.

The second aspect is even more worrisome, when the initial or recurring misalignment between the optical beams boresights is unknown and of several tenth or hundredth beamwidths. Initially a brute-force, sequential, raster scan approach was proposed leading however to unpractical acquisition times. Variants were conceived, see e.g. [7], on the spatial scanning approach to decrease the acquisition times, but these remained quite high. Substantial work has been produced worldwide on the 'all optical' solutions to pointing acquisition and tracking (PAT) which often resulted in quite sophisticated [8], complex and costly systems. All this plus the fall off in the demand for commercial space communication has, 'de facto', considerably contributed, over the past few years, to discourage further development of this technology.

This author believes that combining RF and optical technologies, instead of insisting on an 'all optical' approach, may lead to solutions which are more acceptable from a technology-risk and cost viewpoints.

Indeed, the acquisition problems are bound to become even worse with the upcoming distributed space assets characterized by time-evolving spatial geometries and the requirement for very rapid handover, in the data transfer from any satellite of the group to any other in visibility, to maximize the data volume transfer per unit time.

In this scenario, system techniques are sought enabling an effective and quasi-instantaneous narrowing of the angular acquisition cell of the partner satellite with which to establish two-way wideband communications via optical ISL.

The proposed approach will be described making reference to an hypothetical constellation system, with satellites injected in multiple equal altitude orbits but different orbital planes. It is also assumed that the mission requirements would imply the sequential, but near continuous, transfer of high speed data flow between satellites in mutual visibility, and that the switching time from one satellite to the next would be minimized. The ISL will be implemented using optical transceivers and telescopes driven by a dual gimbal system – a mature technology- capable of fine pointing performance. The operational scenario implies that the distance, bearing and depression angles from one satellite to all the nearby ones will be generally different and time-varying with the satellites' orbital evolution. An optical telescope, around 10 cm in diameter, will produce approximately an 8 μrad beamwidth. The open loop initialization should bring the optical tracker boresight close to K times the optical beamwidth, with K being in the 5 to 10 range to get a fair probability of a rapid lock-on the partner satellite.

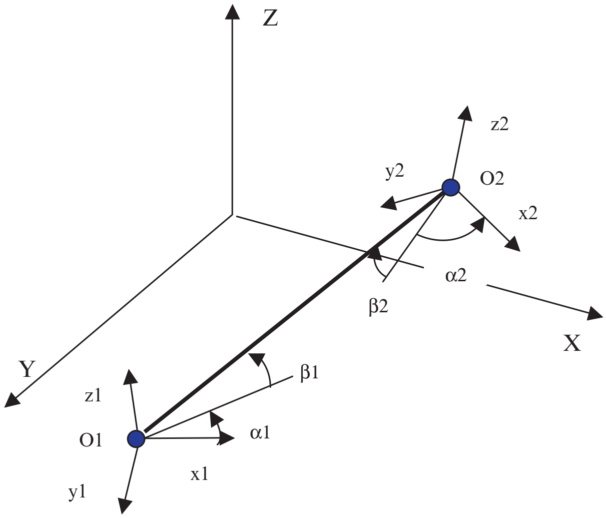
3 GPS Receivers and Low Datarate Links for Fast Open Loop Acquisition

Almost all modern satellites, both large and small, do carry GPS receivers for orbital position restitution and timing distribution Some satellites even carry a GPS receiver with four antennas placed on the tips of two interferometric arms as an additional platform attitude sensor, although this solution has been adopted with less then expected favour because ultimate performance is achieved with difficulty, due to spacecraft-induced multipath, and the increase in the receiving elements (large flare angle horns) dimensions resulting from attempts to control the dangerous multipath effects. For the proposed solution, however, we have considered satellites equipped with basic GPS receivers only.

The starting idea to solve the optical ISL initial acquisition problems is to fully exploit the GPS / GNSS navigation signal. Both satellites will carry a GPS receiver and an estimator of its spatial position in a common three-axis system, e.g. the standard inertial coordinate system. Each spacecraft will then periodically broadcast, using a near omnidirectional antenna operating at any convenient frequency, a data packet consisting of a satellite identifier followed by continuously updated three-dimensional position and speed data in the common reference system. The timing for the information exchange is proposed to be controlled in a master-slaves organization of the constellation. Thus all satellites know the three-dimensional position, in space, of all the others as well as their own position. In order to derive from these data the bearing and elevation angle, for open loop pointing the boresight of the optical communication system, the satellite must also know the orientation of the body axes w.r.t. the common coordinate system. Purely for the sake of clarity, the system geometry is shown in Fig. 1, for two satellites only.

The open loop pointing error of a gimballed optics with respect to the required direction O1–O2 results from the combination of three contributions:

- the estimate of the orbital point O1;
- the estimate of the orbital point O2, relayed from satellite #2 to satellite #1;
- the error in the attitude determination of x1,y1,z1 w.r.t. the reference coordinate system X.Y.Z



X,Y,Z: common coordinate system
x1,y1,z1; and x2,y2,z2: body coordinate axes
O1, O2: satellites' instantaneous orbital position
α1, β1; α2, β2; bearing and depression angles of O1-O2 measured in body coordinates by spacecraft #1 and #2

Fig. 1. System geometry.

The first two contributions are quite small indeed, around 10 m each, even using the C-code. This means an angular error of the order of 20 μrad for an intersatellite distance of 1000 km, which however rapidly decreases with increasing ISL distances.

The spacecraft attitude error is a cause of concern. One possibility is to use the platform' own attitude sensors (e.g. Star, Sun, Earth or a combination thereof) but the achievement of sub-mrad pointing error will require accurate and costly sensors, usually available only on larger and sophisticated spacecraft. For example state-of-the art star sensors can provide attitude measurement accuracies around 0.05 mrad. Combining this performance with the orbital position inaccuracies, one gets a boresight error estimate of around 70–80 μrads, which is 10 times the optical beamwidth. By open loop directing the optical telescope boresight according to the bearing and depression angles so computed, a fine acquistion can be performed using the optical telescope's own APT (Acquisition, Pointing and Tracking) subsystem. For ISL distances shorter than 1000 km, and down to 100 km, the error in the estimate of the vector joining the two satellites becomes significant (between 20 and 200 μrad, single measurement) but can be reduced, by one order of magnitude, applying smoothing techniques to the sequences of position, speed and attitude data of the two spacecraft.

The block diagram of the GPS-aided open loop driving of the optical telescope is shown in Fig. 2.

The specific equipment required for implementong the optical telescope open loop fast repointing, are the low data rate X_band transceiver with the associated

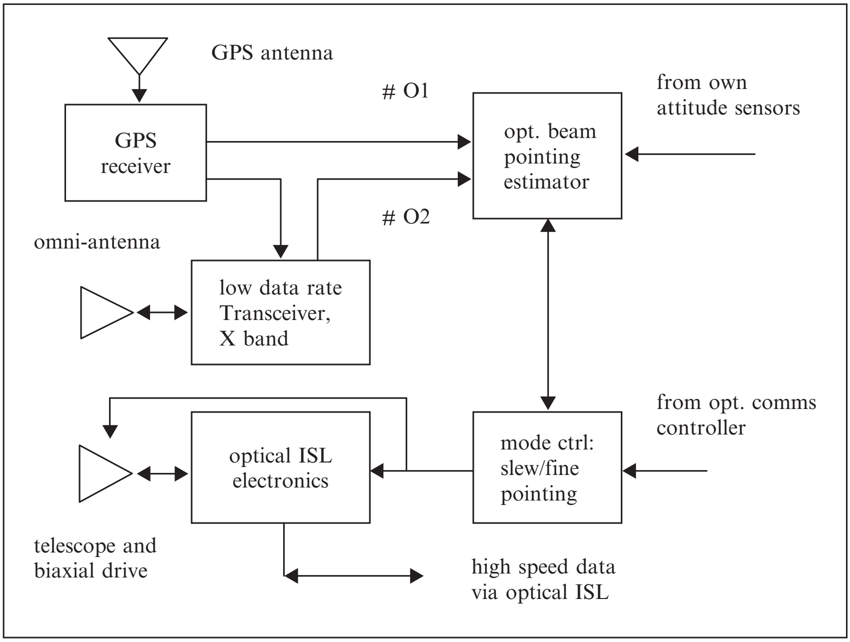


Fig. 2. Block diagram of GPS-aided open loop optical ISL pointing.

omni directional antenna and the optical beam pointing estimator. The antenna is a small bi_cone with a toroidal beam 360° × 20°; the X_band transceiver operates in simplex mode – that is transmission and reception are not simultaneous- and features a duplexer, a 1 W output power stage, a LNA and BPSK modulator and demodulator. The transceiver emits every 5 seconds, and for a duration of 1 second, a packet of about 100 bit, generated by the GPS receiver at a rate of 100 bps. The transceiver receives, instead, a sequence of 1 sec. data packets- at a rate of 100 bps- corresponding to the emission of the nearby satellites broadcasting their spatial coordinates. The timing, coordinated by the 'master satellite' takes into account the required guard times between bursts emissions.

The optical beam estimator is a simple microprocessor-based circuit that receives the position and speed data from the local GPS receiver, the remote GPS receivers hosted in the other satellites, and the locally generated data from the satellite attitude sensors. The circuit computes – by means of software routines mainly involving matrix operations, filtering and smoothing – the bearing and depression angles as imput to the optical telescope biaxal drive. For very wide repointing when passing from one satellite to the next, the circuit computes also the time sequence of the pointing coordinates during the transient to optimize the latter.

The link budgets shows that a 1 W RF power at X_band is sufficient to transmit 100 bps data rate signals in BPSK over a free space distance of up to 5000 km – the maximum practical L.O.S. between two LEO satellites. The provision of a simple coding will then provide the required margin to achieve an error rate of 10^-5 which is adequate for this application.

Obviously, the use of the auxiliary, small, X_band transceiver can be exploited for other communication functions, in which case the signal bandwidth as well as other system parameters will have to be adapted to the new requirements.

4 Interferometry Based System for Fast Acquisition and Tracking

Relying on top performance platform attitude sensors does not seem fit for the micro e minisats targeting the medium-low cost market. Indeed many of these low cost satellite, even those carrying out missions that may justify the use of optical ISL, are characterized by less than top performance Attitude Control Systems. Accordingly, other means have been considered to achieve a fast open-loop initialization of the optical APT. It is envisaged that many applications of mini, micro and nanosatellites constellations requiring very high datarates transfers might concern smaller inter-satellite distances, thus smaller telescope diameters, say in the 1 cm range or less providing some 80 μrad optical beamwidth.

One possible approach is to make resort to an interferometric system exploiting a signal broadcast by the partner satellite. The interferometric system, which has no moving parts, must have a 360° coverage in azimuth and some 20° to 30° in the elevation plane, to cope with the ambiguities in the depression angle. The sensitivity of the interferometric system depends on the arm length and operating frequency. Concerning the latter, either the X or Ku band, or even the millimeter band, are preferred to lower frequencies for the following reasons:

– greater interferometer sensitivity for a given baseline length;
– smaller antennas for a given design beamwidth.

With a baseline of 10 wavelengths at X_band (that is an interferometer arm length around 30 cm), a phase detector and associated processor capable of 0.006° sensitivity, the error in evaluating the angle of arrival of the incoming beacon signal emitted by the partner satellite will be in the range of 0.15 mrad. The error contribution due to the Doppler effect – the two spacecraft have a non-zero relative speed- is negligeable. The interferometer directly provides the bearing and depression angles of the incoming wavefront measured in body coordinates: and these can be used to drive the optical telescope dual gimbal system. Ambiguity problems, typical of long baseline interferometers, will be solved implementing a dual baseline, i.e. coarse-fine, geometry.

The potential advantage of the interferometric system is that one could eliminate the optical system pointing and tracking system by implementing a software-based optics beam pointing estimation algorithm. Indeed, the nearby satellites move with a relative velocity which can be relatively low-as in the case of a formation deployed throughout a quite limited spatial volume- or as high as twice the spacecraft orbital speed - as in the case of a constellation with satellites coarsely distributed around Earth. The relative speed justifies using an adaptive – proportional plus derivative-software-based tracker (e.g. an alpha-beta tracker or other efficient algorithms) where the individual measuremenents, performed with the interferometer, are collected and processed to extrapolate the near term relative satellite motions from actual measurements and the recent past history. This processing efficiently implements a smoothing of the data points, therefore the prediction accuracy is estimated to be substantially better than the 0.15 mrad of a single, isolated, measurement-based evaluation.

The physical implementation of the interferometric system will depend on the mini- micro or nanosatellite dimensions, most of which have a cube-like shape and while the sides are not generally available because reserved to other subsystems, the satellite wedges, or the edges of the side panels, can be- instead - cleverly used. To provide a 360° coverage in azimuth all four side panels could carry a thin dielectric strip with printed patch antennas implementing the short and long interferometer baseline. To provide the 20° or 30° coverage in the vertical plane, all four panels will also carry a printed circuit strip at 90° w.r.t. the other. A possible arrangements is given in Fig. 3, showing just one of the four side panels of the satellite.

The horizontal and vertical interferometer RF channels are kept separated. The switching between the short and long baselines of each quadrant, as well as the sequential switching of the four interferometer quadrants is made with PIN diode switches driven by a control logic. A simplified functional diagram of each interferometer arm is given in Fig. 4, which is valid for both the azimuth and elevation interferometer arms, following a highly modular approach. The beat signal resulting from the mixing of the three signals received from the three patch antennas with a carrier generated by a local oscillator are input to a phase detector a pair-at-a-time. The signals' selection is made in a SPDT PIN switch. The phase detector output is thus proportional either to the bearing angle or to the depression angle.

In a constellation environment a time-shared operation of the tranmit and receive tasks can be easily managed: a repetitive time frame is defined and divided in N slots where N is the number of satellites mutually and simultaneously visible from any satellite in the constellation. Each satellite transmits sequentially a signal during one

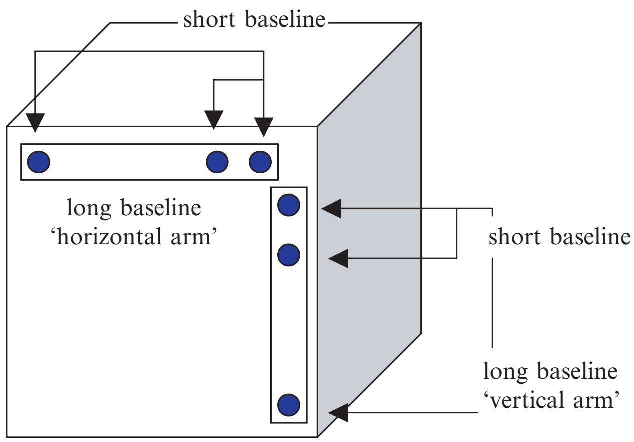


Fig. 3. Possible arrangement of long and short baseline interferometer antenna elements on the satellite side panels.

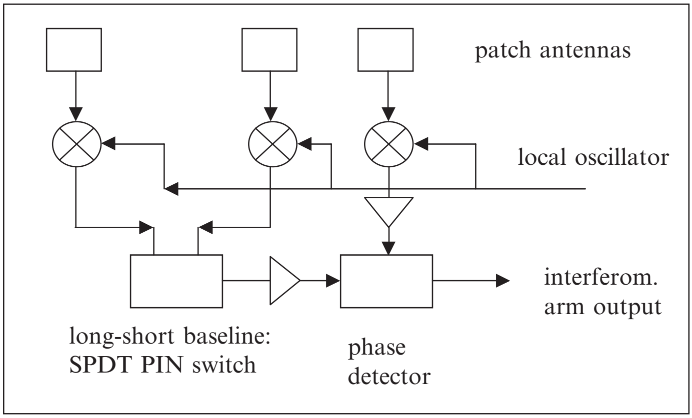


Fig. 4. Schematics of the azimuth or elevation interferometer arm.

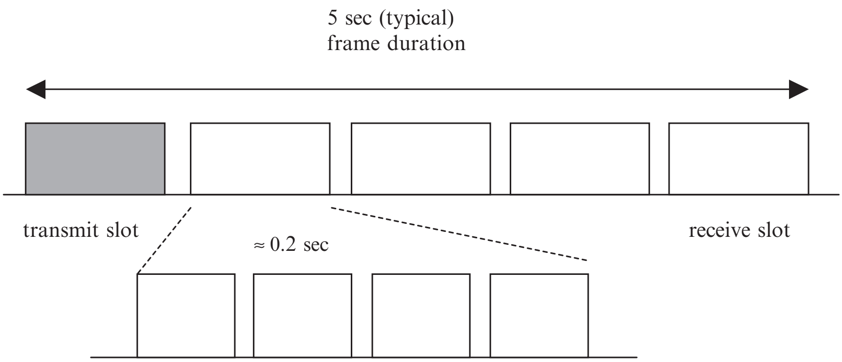


Fig. 5. Sample system timing.

time slots and can receive the other N-1 signals emitted by the other N_1 satellites in the corresponding time slots. During each 'receiving slots' the interferometer performs the measurement of the bearing and depression angles of the incoming wave front emitted by the M-th satellite. The quadrant switching is performed within each 'receive slot' and the four sequential signals at the output of the phase detectors are compared to sort out ambiguities and gross errors.

A sample system timing is shown in Fig. 5 illustrating the subdivision of each 'receiving slot' into four sub-slots for parallel evaluation of the side panels horizontal and vertical interferometer arms.

A simplified block diagram of the satellite interferometer subsystem as shown in Fig. 6.

One of the four 'horizontal arms' outputs, designated as the most likely, is then used to compute the bearing angle. A similar process is performed in parallel for the 'vertical arms', resulting in the evaluation of the depression angle. The data are temporarily stored in a bank of N_1 small memories in order to be further processed.

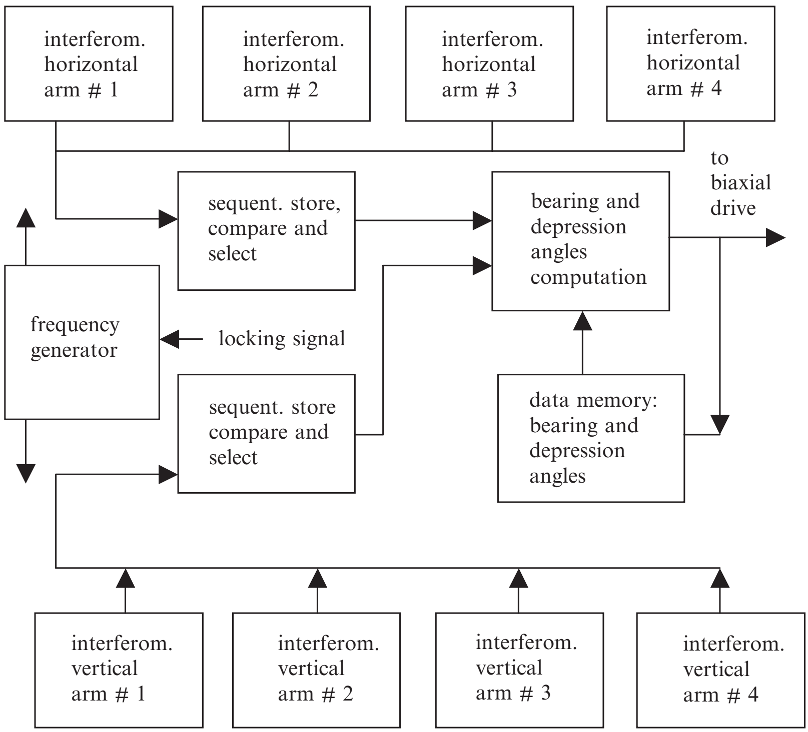


Fig. 6. Interferometer system block diagram.

The outputs from the horizontal and vertical arms of the interferometer are then input to a software-based estimator implementing advanced filtering and smoothing techniques, making use of past evaluations too, and the output is sent to the dual gimbal drive of the optical telescope.

Concerning the physical implementation of this RF wavefront angle-of-arrival sensor system, the four plus four printed circuit strip carrying the three X_band patch elements will have a width of around 10mm. The strip will also integrate the mixers, PIN switch, IF amplifiers and comparator, taking advantage of the high integration and miniaturization level achieved by RF and IF parts developed for the mass market, and that can be adapted to operate in the space environment provided suitable precautions are adopted. The arm assembly will thus take the shape of a rectangular cross-section rod, which can be either laid on the edge of the side panels or on the wedges of the satellite.

The local oscillator feeding all eight interferometer arms is phase locked to the sum signal picked-up either by a combiner of all antenna patches distributed around the satellite or by a dedicated antenna element. The carrier so generated will then be simply distributed by means of a times-eight divider without any worry as to path-length equalization since the three mixers of each arm are fed in-phase by a suitable design of the paths inside the rectangular cross-section rod.

Preliminary link budgets seem to point to the feasibility of operating the interferometer by transmitting a 0.5 W X_band carrier via the bicone antenna from the partner satellite, and assuming hemispherical beamshapes for the interferometer' arms patch elements.

5 Combined MW and Optical Technologies for Microsatellite Fast Acquisition and Tracking

It should be noted that, in this paper, we focus on existing and near-term plans for implementing formations or satellite constellations featuring augnificant intersatellite information transfers. The problem of fast satellite acquisition and beam repointing when using optical ISL in close range formations, has its own specificities which are summarized below.

– sophisticated APT systems are undesirable for cost and system integration reasons. This may indeed rule out the interferometric system described above, which seems more suitable for medium-class minisatellites;
– the platform attitude determination sensors, usually chosen to meet the essential Mission requirements, may be unsuited to support open loop pointing of the optical beam. Indeed many microsatellites are designed with platform pointing accuracies in the 0.1° to 1° range, which are orders of magnitude greater than the optical beamwidth. Indeed the latter, if designed to support – over distances in the 10–100 km range- datarates of several hundred Mbps, will have a size well under 0.01°.

A 100:1 or 10000:1 ratio in the scan cell widths to optical beamwidth ratio implies scanning, or handover times for the acquisition of the co-operating satellite, which are too long. One solution is to adopt multiple, wider, optical beams either on transmit or receive, as basically proposed in [5], [12]. However that solution penalizes the data rates that can be transmitted over the ISL, without increasing the tranmitted optical powers, something which is not compatible with the DC power budget typically available in most microsatellites.

A possible solution comes from revisiting a concept illustrated in [9]. The system configuration of that patent makes reference to a pair of satellites, neither of which knows its attitude to a high degree of accuracy but both of which are nevertheless equipped with GPS receiver. Each satellite sends its own position to the other, via a radio-link, whereupon each satellite computes the vector joining the two satellites, as described in paragraph 3. In addition, each satellite is equipped with a dual gimballed antenna which acquires and tracks the RF emissions of the other satellite. The gimbal angles are taken as a measure of the tracker boresight angles in body coordinates. From a comparison between the computed angles (body perfectly aligned with the reference axes) and the measured angles, the patent claims that it is possible to compute the spacecraft attitude error: which is indeed conceptually correct. However instead of using the system to derive the spacecraft pointing error, we propose a different embodiment.

The basic idea is to integrate – in a single multipurpose Unit- a coarse, fast, acquisition system working in the microwave bands and a fine acquisition and tracking system working in the optical bands. In must be said that the open literature reports sparse examples of Intersatellite PAT combining optical and microwave frequencies, one of which is found in [10], though applied to stratospheric platforms and mainly to combat fading.

The combined system will first search, and coarse acquire, a RF beacon emitted br the partner satellite, then will switch to the optical PAT which is in charge of the fine optical signal acquisition and tracking. To this end the optical dynamically repointable telescope will also integrate a microvave small planar antenna designed to generate both a sum beam, substantially larger than that of the optical telescope, and two 'difference' signals proportional to the error between the instantaneous l.o.s. between the two satellites and the commanded mechanical antenna boresight.

During the initial acquisition phase, the microvave system is active while the optical system is in stand-by. A nulling system is applied to the microvave antenna error outputs and to the dual gimbal drive, as in a conventional tracker; therefore the mechanical boresight will gradually move in the direction to reduce the misalignenent between the boresight and the instantaneous l.o.s. When the misalignment has been reduced to a very small value, then the microvave system goes in stand-by and the optical system is activated. The 'optical' PAT will then work within rather narrow angular boundaries, completing the fine angular acquisition then passing into the fine tracking mode. The microwave system will then be put on hold till a new wide angle acquisition in occasion of satellite handover.

It must be noted that the system operation can do without the transfer of information about the two satellites orbital position data obtained from the space-borne GPS receivers: indeed the operation of the coarse and fine nulling systems does only rely on the sequential emission, by the partner satellite, of microwave and optical beacons, either unmodulated or modulated. However, the availability of the intersatellite l.o.s. vector, if computed on board, specially in the case of under-instrumented microsatellites, can be used to improve the attitude error estimate and, ultimately, the microsatellite attitude control performance. This might be instrumental for critical Missions, such as the Earth Observation ones, implemented by means of space-distributed assets.

Figure 7 shows an Artist's view of a combined microwave-optical ISL terminal for microsatellites. The cylindrical section, with a diameter around 10 cm, includes a four-quadrant planar passive array and a beamformer providing a sum and two difference signals. The choice of an operating frequency in the 26 GHz band would give component beamswidths around 15°: which is very convenient for fast satellite acquisition. The 45° flat mirror is steered in azimuth by + – 180° and in elevation by + – 15° by means of two small drive motors which are active in all operating modes. Since the flat reflector will rotate w.r.t. the fixed array antenna, the use of circular polarization is mandatory. At the center of the flat array there is an hole for passing signals in the optical bands: see Fig. 8. The laser transmitter and the optical detector are housed in the lower part of the fixed cylindrical body: an optical prism, or dichroic filter, will separate the tramsmit from the receive optical frequencies allowing to share the same focal region.

Fig. 7. Artist's view of the combined microwave-optical ILS terminal for microsatellites.

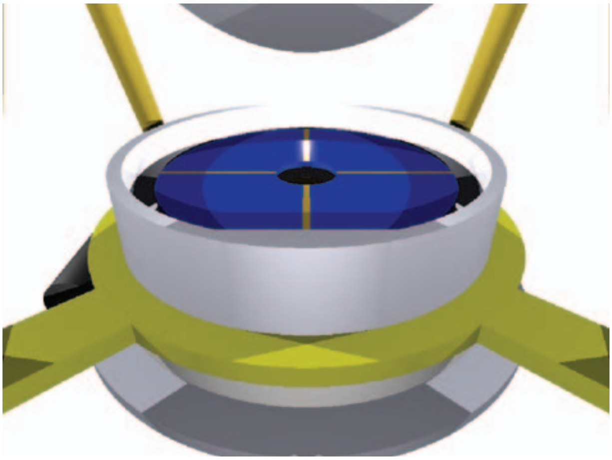


Fig. 8. A detail of the fixed cylindrical section housing the MW flat array and the optical transceiver head.

The flat reflector, which is polished to an optical quality, reflects the optical signals establishing the correct origin to destination paths, while mirror steering, under control of the APT, allows performing both fine acquisition and tracking of the partner satellite.

The small dimensions of the assembly are compatible with micro and nanosatellites. It should be borne in mind, according to the previous discussions, that if the terminal is operated alòong with on-board GPS receivers, it can also provide attitude determination data: which would be an important by-product and microsatellite performance-enhancer.

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